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MEng: Electrical Engineering in Smart Grid

Investigation of the Communication Protocol for the Power Plant Controller

(Dissertation)

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DECLARATION

I, Rayner Johnson, declare that the contents of this proposal represent my own work and that the dissertation has not been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

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Abstract

This research investigates the communication of photovoltaic (PV) inverters to Power Plant Controllers (PPC). Currently, the only communication option is to use the Modbus protocol, as all inverter manufacturers provide Modbus-compatible communication modules to the PV inverters. With the worldwide adoption of the International Electrotechnical Committee (IEC) 61850 standard, the MMS protocol is compared to the Modbus protocol. This investigation involves a simulation of PV systems compiled on a real-time digital simulator (RTDS) NovaCor machine. This simulation can interact with external Intelligent Electronic Devices (IEDs) through a communication card called GTNETx2. The PPC is configured using the SEL 3555 RTAC as the device and interacts with the simulation. The first iteration of the investigation is compiled using Modbus, and the second iteration modifies the communication integration with the IEC 61850 MMS protocol. Data is captured and transmitted between the RTDS NovaCor GTNETx2 card (simulation) and the SEL 3555 RTAC (PPC). This data provides insights analysed using packet analyzer software called Wireshark and IED Explorer. Interpreting the data is based on comparing the two protocols and identifying the efficiencies and functionalities of each protocol. The IEC 61850 MMS protocol displays advanced functionality such as timestamping, quality data bits, reporting, and complex adoption towards the power systems use case. However, larger packet files and more complicated configuration causes distinct disadvantages. The investigation extends to the implementation of data monitoring to develop the interpretations used for comparison.

Keywords

Advanced communication, Power Plant Controller (PPC), IEC 61850, Modbus.

Nomenclature

AC – Alternating Current

Bit – Single binary number (smallest unit of data a computer can store)

Byte – Consists of 8 bits of data

CDC – Common Data Classes

CSI – Current Source Inverters

DA – Data Attributes

DC – Direct Current

DER – Distributed Energy Resources

DO – Data Objects

DPC – Double Point Controllable

DPS – Double Point Status

GCC – Grid Code Compliance

GTNET – Real-time Communication Card for RTDS

GUI – Graphical User Interface

HIL – Hardware-In-The-Loop Simulation

IEC – International Electrotechnical Commission

IED – Intelligent Electronic Device

IGBT – Insulated Gate Bipolar Transistor

IP – Internet Protocol

LAN – Local Area Network

LCOE – Levelized Cost of Energy

LN – Logical Nodes

MMS – Manufacturing Message Specification

Modbus – Modbus Communication Protocol

MPPT – Maximum Power Point Tracking

OSI – Open Systems Interconnection

PLL – Phase Lock Loop

POI – Point of Interconnection

PPC – Power Plant Controller

Protocol – A set of formal rules describing how to transmit and exchange data

PV – Photovoltaic

RMU – Ring Main Unit

RTAC – Real-Time Automation Controller

RTDS – Real Time Digital Simulator

SAS – Substation Automation System

SCADA – Supervisory Control and Data Acquisition

SPC – Single Point Controllable

SPS – Single Point Status

TCP – Transmission Control Protocol

VAR – Reactive Power

VSI – Voltage String Inverters

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Chapter 1: Introduction

1.1 Introduction

The power grid consists of three primary components: generating plants, the transmission grid, and the distribution network. Traditionally, power is generated in large quantities and flows from generation through transmission before reaching consumers via distribution. With the increasing adoption of renewable energy, power is now commonly injected at various stages of the power grid, leading to distributed energy resources (DERs). In recent years, there has been a significant focus on power quality and the integration of renewable energy technologies onto power grids (Santiago Benavides-Cordoba, 2019), (Ashutosh Kumar Tiwari, 2021). These renewable plants must contribute to a stable and healthy grid by providing active power control, reactive power control, frequency control, and voltage regulation (Kumar, 2021). Therefore, local utilities enforce grid code requirements to ensure renewable energy plants can maintain grid stability (Santoshi B, 2019). For these plants to provide support, they must communicate effectively with the utility, responding promptly to operational commands.

The flow of information used to control and monitor data is referred to as supervisor control and data acquisition (SCADA). The grid operators are based in a central headquarters and monitor the status of the national grid. Communication between various stages of the power grid and the systems connected to it is done via defined protocols. Protocols provide the structure for how messages interact with data. These messages are to be encoded and decoded by the transmitting and receiving devices accordingly. (Adamiak, 2009). The development and implementation of the IEC 61850 standard globally has been noted in (Apostolov, 2006) and (Yang C. &., 2024). However, the communication between the PV inverters to date are only compatible with Modbus. PV plants utilise a device referred to as the Power Plant Controller. This device is responsible for coordinating the production of the PV plant. Therefore, the PPC receive setpoints from the grid and provide control through communicating with the PV inverters to obtain the desirable performance.

This study looks at providing a comparison between two protocols. Firstly, the protocol currently implemented in utility PV plants worldwide is Modbus. The second protocol is the Manufacturing Message Specification (MMS), defined by the IEC 61850. The MMS protocol was selected due to the Substation Automation System (SAS) often using MMS protocol for bay level communication. MMS protocol is used in bay-level communication due to the client-server model it is built upon. This is very similar to that seen in Modbus and therefore, the comparison is not based on the model of the two protocols but the structure that each protocol is built upon. To achieve a comparison study between the two protocols, a simulation including PV systems connected to a power grid is compiled on RSCAD FX (a software developed by RTDS for simulations running on the NovaCor). A simulation based on the Modbus protocol is then modified to be executed with the MMS protocol. The NovaCor and the SEL RTAC communication packets are captured and analysed. The literature is focused on the communication protocols Modbus and MMS as well as providing insight into the implementation of PPC in utility-scale PV systems.

1.2 Awareness of the problem

Modbus protocol was designed in 1979 to use programmable logic controllers (PLCs). Modbus gained popularity and familiarity in the automation industry and has been successfully developed by many manufacturers. However, the IEC 61850 standard released a list of protocols implemented in Intelligent Electronic Devices that comprise the substation automation system. The IEC 61850 is designed for use within the electricity and energy industry. Therefore, the structure of the standard hints towards having the foundation for a more suitable protocol to be implemented in inverter communication to the PPC. Thus, this research investigates the differences between these protocols in monitoring PV inverter output communication to a PPC.

1.3 Problem statement

Currently, all PV inverter equipment manufacturers, such as Sungrow, Huawei, and SMA, only implement Modbus communication modules to interact with the inverter controller. Modbus lacks certain functionality identified in IEC 61850 standard protocols that would hint that the application of the IEC 61850 MMS protocol is suited for the application of communication between a PPC and PV inverter.

Research Question: How can Modbus and MMS communication protocols for power plant controllers be optimized to improve real-time data exchange, operational efficiency, and system reliability, particularly as plant operations become more complex, PV renewable energy sources are integrated, and advanced control systems are used?

1.4 Research aims and objectives.

This research aims to develop a comparison study between the application of Modbus and the IEC 61850 MMS protocol in the communication between the inverter and the PPC. The comparative study details the advantages and disadvantages of each and provides details of the protocol features in the context of PV inverter control.

A PV systems simulation using a SEL 3555 RTAC as a PPC be configured for both the Modbus and IEC 61850 protocols. In completing and compiling the simulation, it is possible to analyze packets of data used to communicate between the PPC and the NovaCor running the real-time simulation model of the PV systems. Using Wireshark packet analyzer software to dissect the Modbus and MMS packets transmitted and received during the simulation.

1.4.1 Aim

Aim to investigate Modbus & MMS communication protocols in power plant control systems that improve data transmission rates, minimize latency, and maintain dependability, particularly for PPC real-time control and monitoring.

1.4.2 Research objectives

By achieving the research objectives listed below, this study aims to contribute to developing advanced protocols for interacting with PV inverters.

- Develop a comprehensive understanding of the application of both Modbus and IEC 61850 MMS protocols
- Review the literature regarding implementing Power Plant Controllers integrating with utility-scale PV inverters.
- Grid Code Compliance: Understand the requirements for PV systems to achieve grid code compliance as the grid and the PV inverters must be coordinated to reach setpoints in given time integrals.

- Simulation and experimentation: Utilizing RSCAD Fx software linked to the RTDS NovaCor machine to compile the PV model connected to the grid with a communication module configured for either protocol.
- Configure the SEL 3555 RTAC to communicate with the PV simulation in Modbus and IEC 61850 MMS.
- Comparative analysis: Conduct a comparison between the two protocols. Create distinguished advantages and disadvantages that, when applied to the scenario, can conclude the preferred protocol.
- Evaluate existing communication protocols (Modbus and IEC 61850 MMS) to determine their suitability for different use cases in power plant operations, such as SCADA systems and distributed energy resource management.
- Investigate communication protocols that can scale as power plants expand (e.g., integrating renewable energy) and adapt to dynamic operational needs.
- Guidelines and recommendations regarding the existing implementation of the Modbus protocol are based on the completed comparative analysis.
- Future direction: Provide suggestions for potential areas of further research.

1.5 Deliverables

The project deliverables are guided by the research objectives and are categorised into the sections listed below:

- Literature review on the current state of technological developments. Technological developments include hardware such as PV inverters and electronic devices and the software configuration required to control PV systems coupled to the power grid.
- Modelling a PPC that communicates with a simulated PV system using Modbus Protocol.
- Configuring the PPC to communicate to the simulated PV system in IEC 61850 MMS protocol.
- Simulation of the PV system configured to communicate with the PPC in Modbus protocol.
- Adjusted simulation of the PV system configured to communicate with the PPC using the IEC 61850 MMS protocol.
- Simulation and testing of both communication protocols for the PPC. This data will be used to investigate the possible adoption of the IEC 61850 MMS protocol for advanced communication between PPC and PV inverters.
- Compose a report based on the research findings and suggest recommendations based on the data collected.
- Compose a dissertation that covers the project scope.
- Produce publications that summarise the project and contribute to the existing body of knowledge. These publications include a conference paper submitted to SAUPEC and a journal article submitted to IEEE Explorer.

1.6 Hypothesis

With the increasing adoption of solar power grids, it is paramount to ensure that these systems contribute to the reliability and stability of the grid. Communicating with the PV inverters provides the basis for connecting PV systems to respond to grid requirements. All inverter manufacturers have implemented the Modbus protocol extensively in the automation industry.

However, the IEC 61850 standard developed a suite of protocols that was explicitly designed to implement IEDs in smart grid evolution. Therefore, the IEC 61850 standard provided rigorous development for the suite of protocols for applying data transfer-related devices managing power transmission. This study aims to investigate the IEC 61850 MMS protocol as a replacement for the current implementation of Modbus in communication with inverter controllers. The functionality of IEC 61850 protocols lists specific data attributes that are not available in the Modbus protocol. The availability of these additional data attributes provides valuable information and suggests that IEC 61850 MMS would be a better-suited protocol for the communication between the PPC and PV inverters.

RTDS provides a suite of software compatible with their real-time digital simulators. Compiling a PV system running on the simulation and communicating with an external PPC in a hardware-in-the-loop configuration enables a benchmark to evaluate the effectiveness of each protocol. The simulation is configured once with the Modbus protocol and then again with the MMS protocol. Capturing packets from each simulation provides data to be analysed for the impact of implementing the IEC 61850 MMS protocol to replace Modbus due to performance and availability of additional data.

1.7 Motivation of the research project

The IEC 61850 standard has been implemented by IEDs in substations. It has been specifically designed for the implementation of control and monitoring power through the power grid. The standard has received much attention, and the further development of IEC 61850-7-420 specifies the application of integrating distributed renewable energy resources. Research suggests that the IEC 61850 suite of protocols provides functionality and performance that enhance communications capabilities between the PPC and PV inverters. However, all PV inverters have only been manufactured using Modbus communication protocols.

Simulating and modelling PV systems compiled on RSCAD Fx and run on the NovaCor RTDS machines allows for testing the advantages and disadvantages associated with each protocol. If the results clearly indicate the IEC 61850 MMS protocol and further research provides assurance, then inverter manufacturers can be guided toward developing updated communication modules that are compatible with IEC 61850.

1.8 Assumptions

Modbus protocol is well established and implemented in PV inverters that are already successful in meeting grid code requirements. However, this familiarity and already established assurance of compatibility is overseeing the opportunity to develop an updated version of communication utilizing the IEC 61850 standard. MMS and Modbus use the TCP/IP protocols for networking and transmission. This research provides insight into the message structure of each protocol itself. The extensive development of the IEC 61850 standard is specifically designed for the complex functionality required for power systems in monitoring and controlling throughout the transmission systems. This intentional design results in additional functionality such as timestamping, quality bits, and interoperability, which is impossible using the Modbus protocol. Capturing the data exchanged between the PPC and simulated PV systems, firstly in a Modbus compatible configuration and then, secondly, in an IEC 61850 MMS configuration, allows the interpretation of the effectiveness of each protocol.

- The Modbus master-slave protocol streamlines network architecture and communication flow but limits scalability and flexibility, particularly in complex, distributed networks.
- Modbus typically assumes a small data payload, usually between 256 and 512 bytes per message. This limits the complexity of the transferred data and may not be suitable for high-bandwidth or large datasets, making it less ideal for modern, data-intensive applications.
- Compared to Modbus, the MMS client-server approach enables more complicated interactions and dynamic communication, with numerous devices possibly submitting requests simultaneously.
- MMS is suited for dynamic applications requiring real-time feedback and control, but it requires a more complex and high-performance communication infrastructure than simpler protocols like Modbus.

1.9 Chapter breakdown

Chapter 1: Introduction

Chapter 1 introduces the role of the PPC in PV systems. Modbus is the current protocol used for communication between the PPC and PV inverters. Introduce the IEC 61850 standard and proposal for replacing the Modbus protocol with the IEC 61850 MMS protocol.

Chapter 2: Literature Review

The literature review is conducted to gain insight into implementing the PPC connecting utility-scale inverters to the power grid. Understanding the knowledge and implementation of both Modbus and MMS is imperative to providing a comparative study. The research literature looks at the message structure defined by both protocols and provides a comprehensive understanding that enables the implementation and analysis of each protocol.

Chapter 3: Lab-Scale Implementation

A simulation is being computed using the RTDS NovaCor machine to run while interfacing it with a PPC. The simulation needs to be conducted in two separate cases, the first compatible with Modbus and the second compatible with MMS. Therefore, the lab-scale implementation details the configuration of the SEL 3555 RTAC to act as a PPC for both Modbus and MMS. The RTDS simulation is adopted from the example cases provided and modified to interact with an IEC 61850 MMS communication module.

Chapter 4: Results and Analysis

Communication data is exchanged between the RTDS NovaCor GTNETx2 card and the SEL 3555 RTAC. Capturing these data packets and using Wireshark to analyse them provides detailed insight into the messages used to implement each protocol. The packets intercepted during the Modbus simulation are compared to packets captured during the second case with the MMS configuration. Furthermore, additional software is used to validate the data displayed to ensure consistency and accuracy. The previous chapter captured all the data from running the two simulations. Data is shown in the Wireshark, and the ability to dissect the information provides insight into the functionality and performance of each protocol. The research literature from Chapter 2 is used to understand and interpret the data for each protocol.

Chapter 6: Conclusion

The results provide a detailed view of the application of each protocol in the context of communication between PPC and PV inverters. The functionalities provided by MMS that Modbus lacks are clearly stated. Further research is suggested to understand the full scope of the functionalities required for inverter control. An additional comparison is also made to utilising the IEC 61850 GOOSE protocol for its faster response time for improved performance in reaching the setpoint.

1.10 Conclusion of Chapter 1

A summary of Chapter 1 covers the introduction to the PV systems communicating with the PPC. It is noted that Modbus is the only protocol currently implemented for communication to inverter controllers. The introduction provides a brief background on the role of the PPC in ensuring that utility PV plants are grid code compliant and contribute to a stable power grid. The introduction introduces the communication protocol Modbus and the IEC 61850 implemented within the substation automation systems. Awareness of the problem is covered in Chapter 1.2 and explains the potential advantage of replacing the inverter communication from Modbus with the IEC 61850 MMS protocol. Chapter 1.3 defines the problem statement that inverter manufacturers have not developed a communication module compatible with IEC 61850 standard protocols, and research suggests the functionality and performance are better suited to the application of inverter controller communication than the legacy protocol, Modbus. Chapter 1.4 provides the research aims and objectives. It lists the objectives that the research covers. Chapter 1.5 expresses the hypothesis that is based on the IEC 61850 MMS protocol being better suited for the application due to enhanced functionality and performance due to the nature of the IEC 61850 standard being explicitly designed for the electrical power grid. The motivation for the research is explained in Chapter 1.6, which introduces the IEC 61850-7-420 chapter of the standard that focuses on integrating DERs. The design of the IEC 61850 standard provides an extensive foundation for communication between devices within the substation. Looking at this successful integration of the IEC 61850, the motivation is to examine the application within PV inverters connecting to the power grid.

Chapter 2 examines the research literature surrounding the key aspects of this research project. These include PV inverters, PPC, the Modbus protocol, and the IEC 61850 MMS protocol.

Chapter 2: Literature Review

2.1 Inverter Topologies

The literature review creates an in-depth review of the method of communicating to utility PV inverters through a PPC to connect to a power grid. Therefore, subsections to the literature review include Inverter Topologies, PPC, Modbus, and IEC 61850. Each of these chapters includes sub-headings that cover specifics that are important in implementing the research project. These sub-headings are listed in the diagram below, noted in Figure 2.1, for further explanation and links to be visualized. Furthermore, simulating a PPC communicating with PV inverters via either Modbus or MMS, as seen in Chapter 3, requires the implementation of RSCAD Fx software running on the NovaCor from RTDS. Utilizing this software enables the opportunity to create a real-time simulation of a PV system that can be linked to an SEL 3555 RTAC in a Hardware-in-the-Loop configuration. Therefore, the literature review also focuses on relevant manuals related to the RSCAD Fx software, the RTDS NovaCor machine, and the SEL 3555 RTAC.

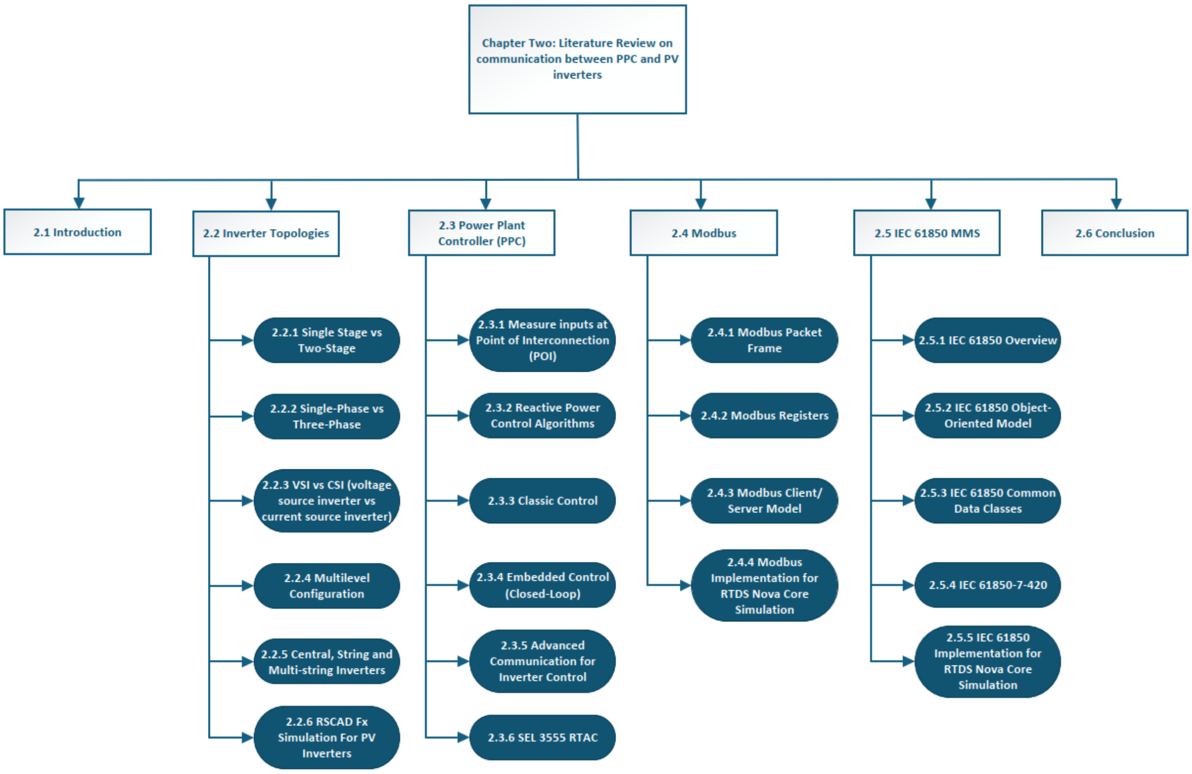

Figure 2.1: Structure of Chapter 2 Flowchart

2.2 Inverter Topologies

Silicon cells in the photovoltaic modules produce a DC output, so the initial input to the PV inverter is always going to be DC. In the case of utility grid-connected PV plants, the output required is AC. However, the inverter topologies differ significantly to achieve this, as seen in the various studied configurations.

2.2.1 Single-Stage vs Two-Stage

The two-stage inverter consists of a DC-to-DC booster converter for the first phase (Huijuan Li, 2012). This focuses on boosting the PV array output DC voltage to achieve the required level for the second stage and performs MPPT. The second stage of the inverter functions to convert DC-to-AC that is compatible with the grid. It also provides volt/var control on the AC output.

Single-stage inverters do not have the DC-to-DC boost converter and only consist of the inverter that controls the real and reactive output as well as generating the AC grid-compatible voltage. Typically, with one less stage, the single-stage inverters are more cost-effective; however, they require a higher voltage to provide volt/var control. The single-stage inverters also face the challenge of more complex control algorithms because of the varying DC voltage due to the nature of photovoltaic generation.

Two-stage inverters is advantageous in the characteristics that it has the additional DC-DC converter that allows better performance of the MPPT. Two-Stage inverters also have a wider tolerance for DC input as well as handle grid-tied control operations more precisely. This comes at a cost of being more complex in build at higher in price. Another disadvantage to the two-stage inverters in comparison to the single-stage inverters is the additional DC-DC converter creates additional energy losses.

An example of the two-stage inverter is shown on the right-hand side of Figure 2.2 below, labelled "b." The single-stage inverter can be seen on the left of Figure 2.2, noted as "a."

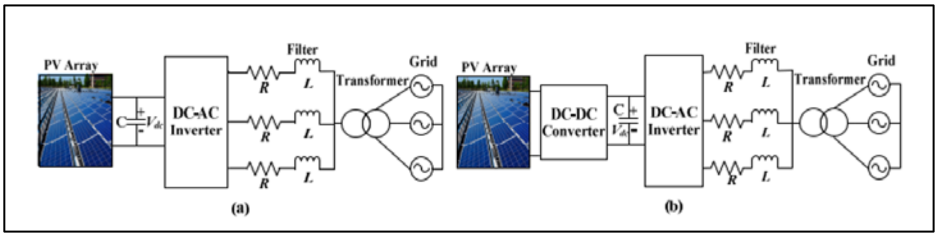

Figure 2.2: Inverter Configuration a) Single Stage & b) Two Stage (Muhammad Yasir Ali Khan, 2020)

2.2.2 Single-Phase vs Three-Phase

The primary function of a PV inverter is to provide AC output. With the worldwide adoption of PV as a generation technology, the applications for PV inverters stretch from residential systems to large utility systems. In residential PV applications, the inverter configuration often provides a single-phase output. In general, for large utility applications, PV inverters have a three-phase output that is synchronized with the grid. (Ana Cabrera-Tobra, 2016). The architecture of the IGBT is arranged in such a manner that provide single-phase or three-phase AC output. Figure 2.3 below shows a general three-phase topology.

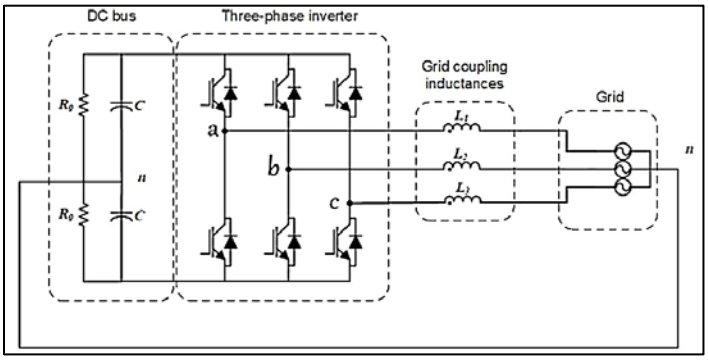

Figure 2.3: Three-phase inverter topology (Santiago Benavides-Cordoba, 2019)

2.2.3 VSI vs CSI (voltage source inverter vs current source inverter)

In terms of inverter classification, according to (Muhammad Yasir Ali Khan, 2020) the most common is the Voltage Source Inverter (VSI). This stems from the Self self-commuted inverter and has two operational modes: Voltage Control Mode and Current Control Mode. This can be seen in the flow chart presented below in Figure 2.4. Line Commutated Inverters (LCI) have been replaced by advanced semiconductor switches such as IGBT as stated by (Ankit, 2018).

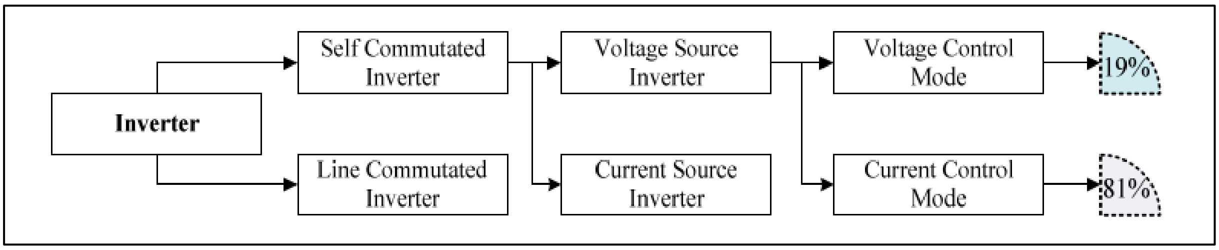

Figure 2.4: Classification of Inverters (Muhammad Yasir Ali Khan, 2020)

2.2.4 Multilevel Configuration

According to (Muhammad Yasir Ali Khan, 2020) The advancements in multi-level inverter configuration in grid-tied inverters have resulted in very efficient performance and advantageous features. Amongst these features include the as the levels increase, the output waveforms also increase.

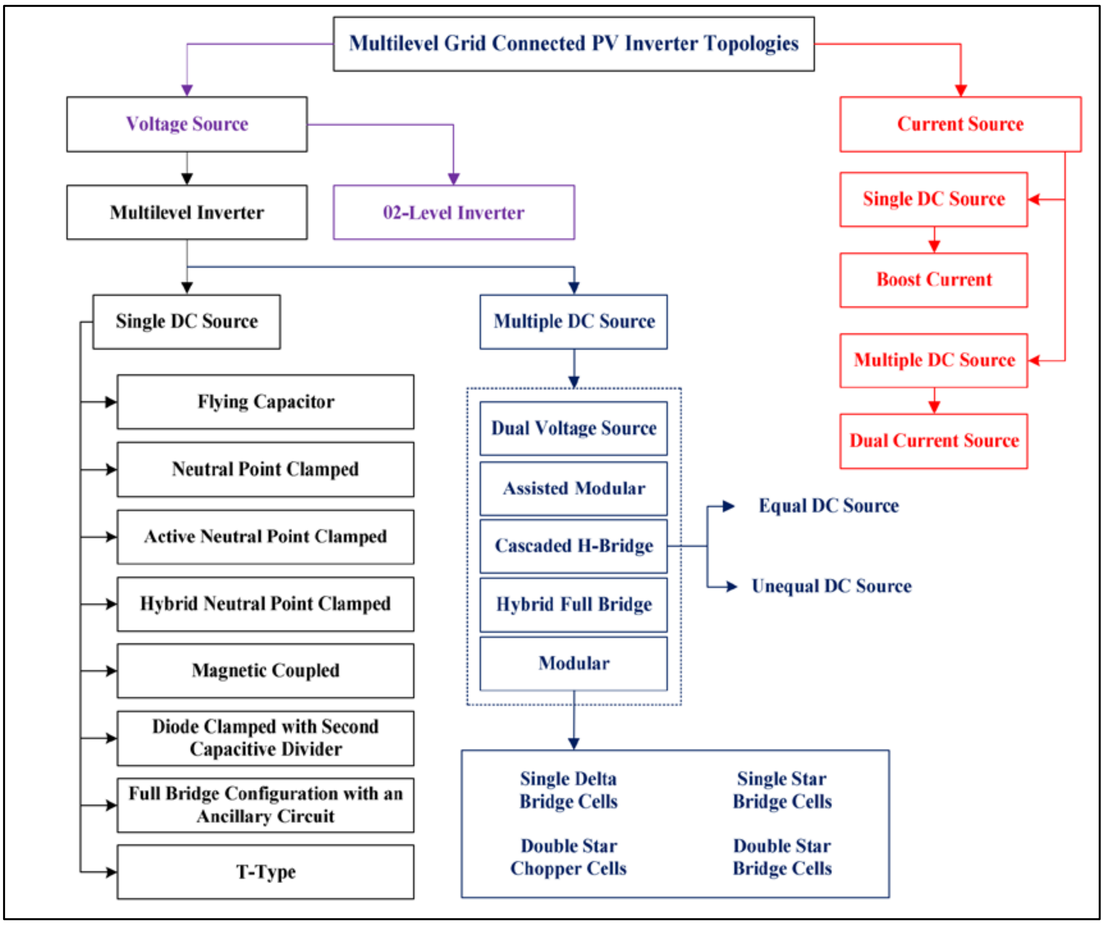

Figure 2.5: Classification of multi-level grid connected Inverters based on power circuit structures (Muhammad Yasir Ali Khan, 2020)

The ability to obtain a pure sinusoidal waveform and has a superior harmonic spectrum. The previous generation is classified as 02-Level Inverters, and the comparison between them and the various topologies that have been introduced by research is displayed in Figure 2.5 above. These classifications each provide various advantages versus disadvantages based on the performance of the proposed architecture.

Important performances that are used to analyse the inverter's capabilities and efficiencies are auxiliary functionalities, efficiency, anti-islanding detection, leakage current, power density and capacity, DC-Link capacitor, switching frequency, and semiconductor devices. The development of the inverter topologies has been at improving these areas of performance so that the connected renewable energy sources can operate efficiently and with superior power quality.

2.2.5 Central, String and Multi-string Inverters

The topology of the PV inverter can further be analysed in terms of central, string, or multistring. These topologies refer to how the inverter collects the DC power from the PV array and converts it to AC output. According to (Ana Cabrera-Tobra, 2016) These topologies must be examined carefully to select the correct one that provides the optimal power in terms of performance under shading, available solar irradiation, and cost impact. The topologies are briefly described below, and Figure 2.6 displays a comparative single-line block diagram.

Central Inverter

The central inverter is often placed centrally with respect to the connected PV arrays that provide all the DC input. These central inverters are often constructed as a single unit along with a transformer and ring main unit (RMU) to connect the AC output cables. The power ratings of the central inverter are the highest available and make use of the cost benefits in large-scale power plants by having a good economy of scale according to (Ana Cabrera-Tobra, 2016). The DC power from the PV strings is normally combined in string combiner boxes to produce fewer inputs to the central inverter. This means that it has lower MPPT across the strings, which could mean lower efficiency on cloudy days. The available level of control is limited to one inverter that comprises a large portion of DC power. This results in less accuracy of control; however, due to their economy of scale, they can produce a better LCOE and are the most common inverter topology used in utility-scale PV power plants currently being developed.

String Inverter

A string inverter connects strings of PV arrays into an MPPT channel. This allows for the most optimal performance in power conversion from the PV array. It requires an inverter per string, and therefore, the effect of implementing this configuration at a utility-scale is costly.

Multi string Inverter

The multi-string inverter uses a DC-to-DC converter for each string and connects multiple strings to the DC-to-AC inverter. Each string can still be connected to an MPPT channel that provides the best performance output.

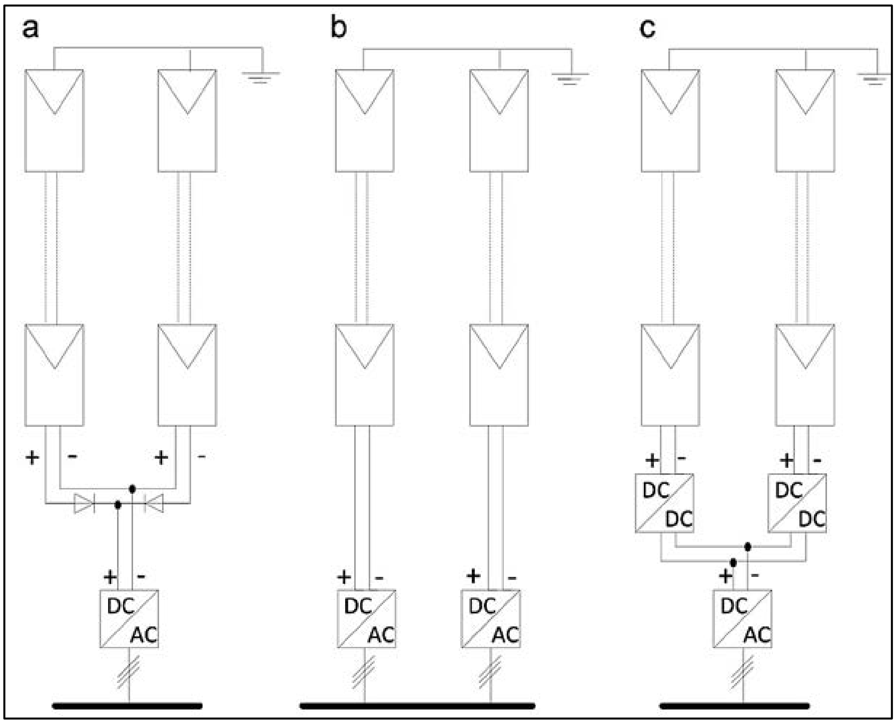

Figure 2.6: Inverter Topologies Single Line Block Diagram (Ana Cabrera-Tobra, 2016)

The performance of these inverter topologies is displayed below in the chart extracted from (Ana Cabrera-Tobra, 2016). This chart divides the main characteristics into categories nested under costs, general characteristics, power losses, and power quality. It is interesting to note that the chart even calculates the costs of cables required to connect the PV arrays to the inverter and the inverter output AC cable. It also considers the installation of the equipment, and although the price for labour varies from country to country, the benchmark for work can be considered. The general characteristic group focuses on robustness, reliability, and MPPT efficiency. Power losses are present in switching, AC, and DC losses, which are undesirable as energy lost cannot generate power. On the other hand, power quality is desirable, and the better the performance of the inverter, the more suitable it is for being grid-tied.

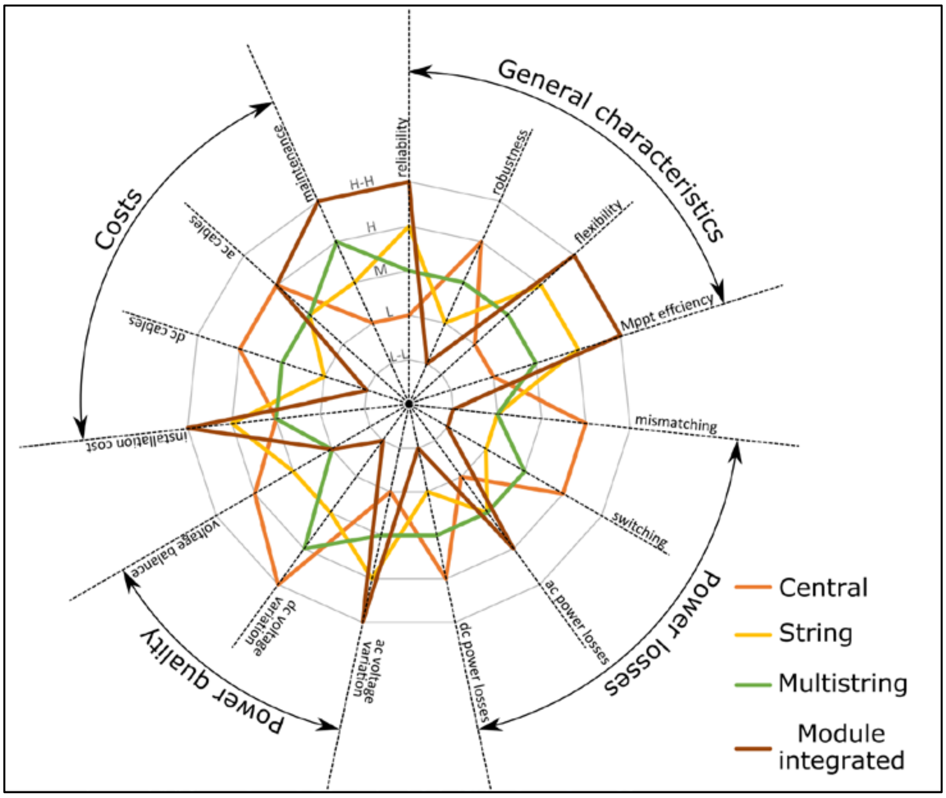

Figure 2.7: Comparison of Characteristics for Inverter Topologies: Central, String, and Multistring taken from (Ana Cabrera-Tobra, 2016)

Based on the literature review, there are a vast number of technological variations in inverter topologies as seen in Figure 2.7 above. To create a model, these technologies must be selected according to the most suitable performance. Since the research is based on reactive power control and the impact of large-scale utility PV plants, a common inverter topology is the multi-string central inverter due to its efficiency and the cost of implementation.

2.2.6 RSCAD FX Simulation for PV Inverters

To simulate a PV system connected to the grid using RSCAD, Fx research is conducted to examine the existing databases already established by RTDS. Navigating to ‘Examples’ in the RSCAD FX software opens a library of ready to use systems already drafted and tested. The example case under Renewables, Power Plant Controller created by Christian Jegues from RTDS, has two PV systems connected to the Grid via a High Voltage (HV) transformer. They are focusing on the PV systems and the configuration required for accurate simulation using the RSCAD Fx model. A screenshot below shows the details of PV System 1 of the model. According to the author, each PV system is scaled down to a single power station. However, this represents multiple power stations simplified for simulating purposes. Each power station includes a combination of a boost converter, inverter, transformer, and switchgear. The PV characteristics are not seen due to space requirements, and it must be noted that the actual PV modules would be on the right of the current snipscreen. The PV characteristics are dependent on irradiation and temperature setpoints. These values then provide the DC power output from the PV modules into the power station. From the previous research, the author has selected the use of a boost converter prior to the inverter stage in his power station configuration. Implementing a transformer after the inverter increases the voltage to reduce energy losses when transmitting power to the grid.

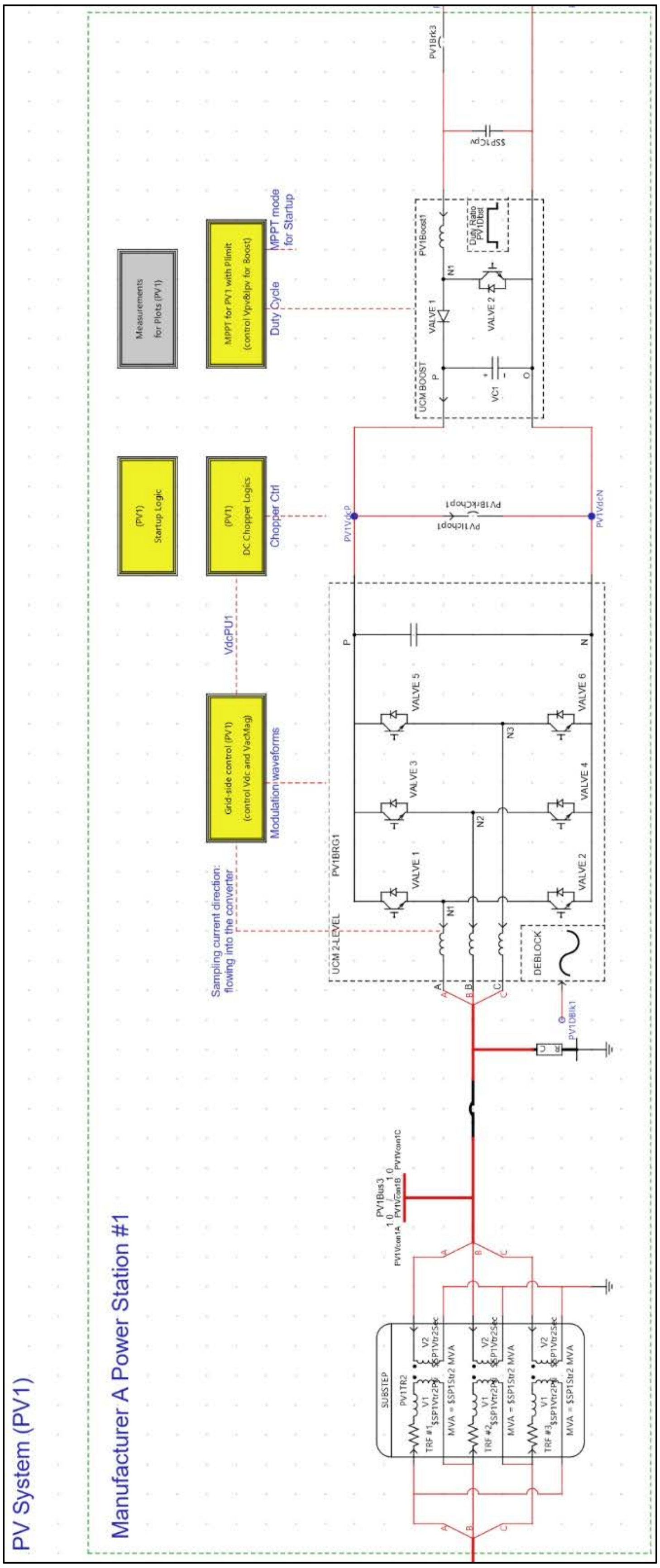

Figure 2.8: RSCAD Power Plant Controller Example by Christian Jeguers PV System 1 Overview

2.3 Power Plant Controller (PPC)

The power plant controller (PPC) provides the controllability required to ensure renewable energy plants perform as local grid codes require. Variable renewable energy generation can pose challenges to the utility specifically concerning frequency and voltage according to (Ashutosh Kumar Tiwari, 2021). Active and reactive power control is critically important to ensure the safe and reliable operation of the grid. The PPC coordinates the control of active and reactive power from the PV inverter. Active and reactive power is generated in the conversion from DC to AC power, and grid-tied inverters must be capable of supporting both lagging and leading reactive power. The PPC is linked to the utility at the point of interconnection (POI); from here, the measured values from the PV plant's output are compared to the desired setpoints defined by the local dispatch center. A basic block diagram inserted from (Ashutosh Kumar Tiwari, 2021) In the attached Figure 2.9, the PV plant's connection with the utility grid is shown below. The PPC communicates the setpoints to the inverters from the measured values at the POI or provided via SCADA from the local dispatch centre.

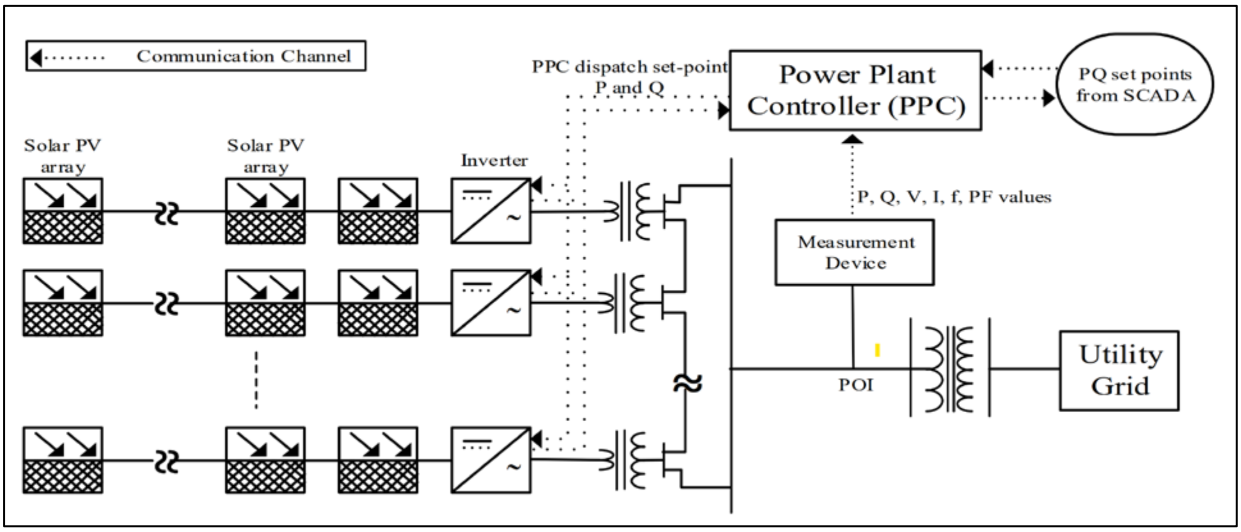

Figure 2.9: Single Line Diagram of Solar Plant with PPC (Ashutosh Kumar Tiwari, 2021)

An algorithm showing the basic functionality parameters for monitoring and controlling a PV plant can be seen below. It is noted the operator provides the setpoints that must be followed. The PPC then monitors the measured values from the POI and the inverters. The PPC then executes a calculation to provide the required functionality for the PV plant to meet the necessary setpoints defined by the utility. This would then require a checkpoint to determine if the grid code constraints have been met. If not, the PPC gets feedback that corrections are needed. Once the grid code constraints have been met, the PPC sends the calculated setpoints to each PV inverter. This happens continuously as power is being generated. The flowchart extracted from (Ashutosh Kumar Tiwari, 2021) is attached below in Figure 2.10.

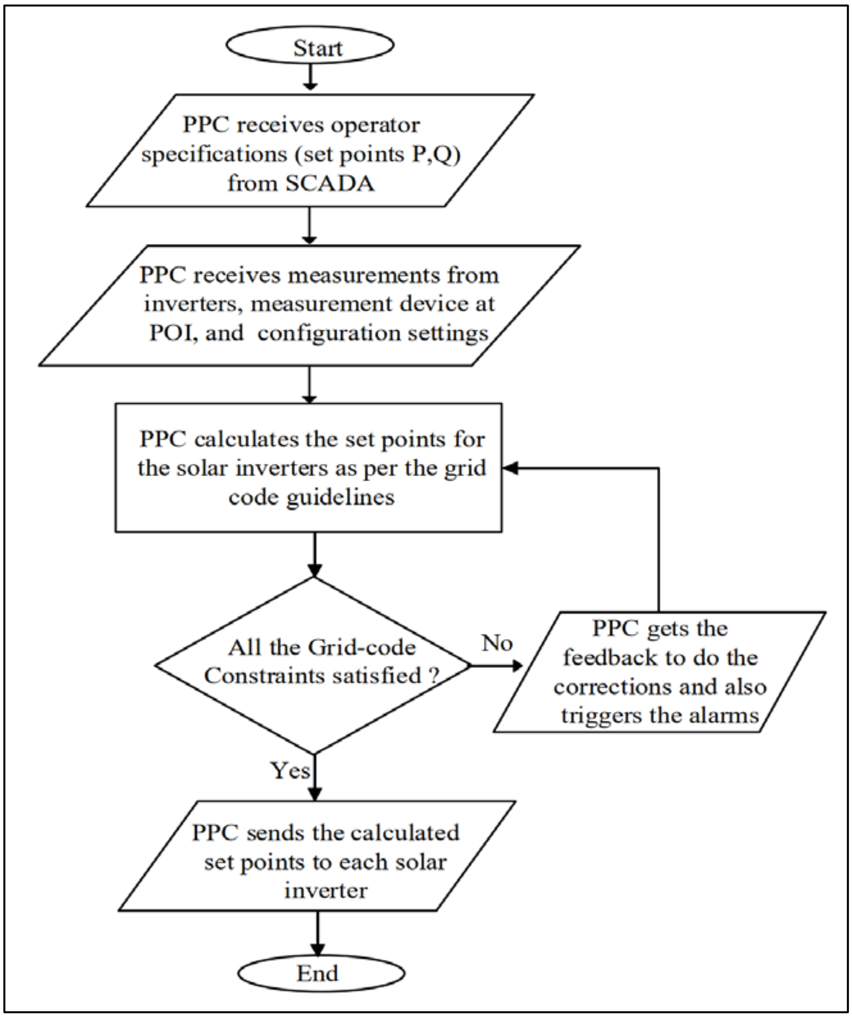

Figure 2.10: Flowchart of PPC Operation at System Level (Naji Rajai Nasri Ama, 2014)

2.3.1 Measure inputs at Point of Interconnection (POI)

The PV plant's performance is consistently analysed to ensure the performance is synchronized with the requirements of the power grid. A Phase Lock Loop (PLL) is an essential block in grid-connected renewable generating inverters, as mentioned in (Naji Rajai Nasri Ama, 2014). As seen in the previous Figure 2.10, the measurement devices are placed at the interconnection (POI) point. The PV plant's performance at the node is analysed to ensure the power quality is suitable for a reliable grid operation. The PLL plays an important role in synchronizing the inverter's output with the grid's voltage and frequency. The PLL achieves this by monitoring the voltage waveform from the grid to determine its frequency and phase angle. The PLL continuously compares these grid parameters to the inverter's output voltage. If required, the PLL commands the inverter to adjust its voltage and or phase angle to match the grid's. Components used in PLL are phase detectors, voltage-controlled oscillators, low-pass filters, reference signals, and control loops.

2.3.2 Reactive Power Control Algorithms

The PV inverter provides reactive power. Various algorithms are presented in the literature that provide solutions for optimizing the reactive power provided by renewable energy plants onto the power grid. Since renewable energy sources are taking up a growing portion of the power generation percentage, their ability to provide active and reactive power is imperative.

The distributed nature of renewable energy sources provides a unique perspective on injecting active and reactive power through multiple nodes within the utility grid. The is a contract to the legacy grid with a very small number of generation plants and, therefore, only a few nodes to provide this control. However, the variable nature of renewable energy sources presents alternative challenges that must be considered, such as reactive power support at night for PV plants.

The droop control has received various adaptations to improve the precise challenges of adopting renewable energy sources onto the power grid. From literature (Gildas Tapsoba, 2018) The applications of droop control can be seen from the control perspective of the PV inverter. Further advancements to Droop Control have been studied, providing mathematical models for each inverter's reactive and active power capabilities. From this model, the reactive or active power source can be derived in a ratio aligned with inverters with higher capacity, providing a higher ratio than those inverters with smaller capacities. Further details regarding the distributed droop control algorithm can be referenced in (Yao Zhang, 2022).

Reactive power control can be divided into two categories. A leading or lagging power factor often defines the categories. A lagging power factor expresses that the current lags the voltage phase and is indicative that capacitive reactive power support is required to balance the system. A leading power factor expresses that the current leads the voltage phase, and inductive reactive power support is needed to balance the system. Due to the nature of industrial and commercial operations, it is typical for the power factor to be lagging due to the inductive motors used.

Initially, reactive power control was provided by ‘classic control’; however, computer advancements provided a new closed-loop control method often termed ‘embedded control’. The differences between classic and embedded control techniques and applications are described in their respective headings.

2.3.3 Classic Control

Classic control for reactive power support can often be described as open-loop control. Some examples of classic control are:

Volt-Var (V-V)

Voltage-Var control operates on the principle of adjusting the PV inverter's reactive power output based on changes in the grid voltage. Modulating the reactive power output maintains a constant voltage profile and regulates the voltage within acceptable limits.

Power Factor Control

PF control adjusts the PV inverter's reactive power output to achieve a target power factor. It ensures that the PV inverter supplies or consumes the required reactive power to maintain the desired power factor, the ratio of real power to apparent power.

Current Control

Current control adjusts the inverter's output current to regulate the reactive power flow. The inverter adjusts its output by monitoring the grid current and comparing it with a reference value to provide the necessary reactive power support.

Droop Control

Droop control is a decentralized control algorithm commonly used in grid-connected inverters. It enables multiple inverters to share the responsibility of reactive power control. Each inverter adjusts its reactive power output based on local voltage and frequency measurements, following a droop characteristic. This allows for better sharing of reactive power control among multiple distributed energy resources.

2.3.4 Embedded Control (Closed-Loop)

Embedded control gains its name from a computational process consisting of complex algorithms based on mathematical models and available data. A few examples of embedded control algorithms are provided below.

Model Predictive Control (MCP)

MPC is an advanced control algorithm that utilizes a mathematical model of the inverter and system constraints to optimize the reactive power output. It predicts the system's future behavior and calculates the optimal reactive power setpoints to minimize a defined cost function, such as voltage deviation or power losses. Using the feedback mechanism, it has a better ability to face uncertainties and disturbances according to (Carlos Bordons, 2018).

Fuzzy Logic Control

Concerning (Oscar Castillo, 2016) fuzzy logic control can be described as a rule-based control algorithm that uses linguistic variables and fuzzy rules to adjust the reactive power output based on inputs such as voltage and frequency measurements. It provides a flexible and adaptive control approach that can handle uncertainties and nonlinearities.

2.3.5 Advanced Communication for Inverter Control

PV inverters use advanced communication for monitoring and control. This communication is based on information technology (IT) and operational technology (OT). It allows the inverter to receive communication from the PPC and respond to setpoints defined by the system operator. Since the inverter is the equipment responsible for frequency, current, voltage, reactive, and active power, control and monitoring are imperative for effective operation. Figure 2.11 below shows the monitoring and control nodes in the PV inverter.

Working with Figure 2.11 below, the diagram displays the PV arrays connecting to the DC capacitor link from left to right. This capacitor is essentially inside the frame of the inverter. At the input to the capacitor, the current and voltage values are monitored, and Ipv and Vpv are denoted. These values are used for MPPT control, and the output reference voltage from the MPPT is monitored for Active Power Control. The DC voltage from the DC link capacitor is also used as a reference for the Active Power Control. The abbreviation LS-PVPP stands for Large-Scale-Photovoltaic Power Plant and the control block represented in the diagram would be very similar to the function of the PPC previously discussed. The active power setpoint is provided to the Active Power Control block as a third input. The active power control then provides voltage and power output to the inverter control block. The inverter Control block then has inputs of reactive power value, as well as an AC voltage and current value monitored from the output of the inverter. The Inverter Control block then uses these inputs to calculate the modulation required in switching the DC to AC inverter.

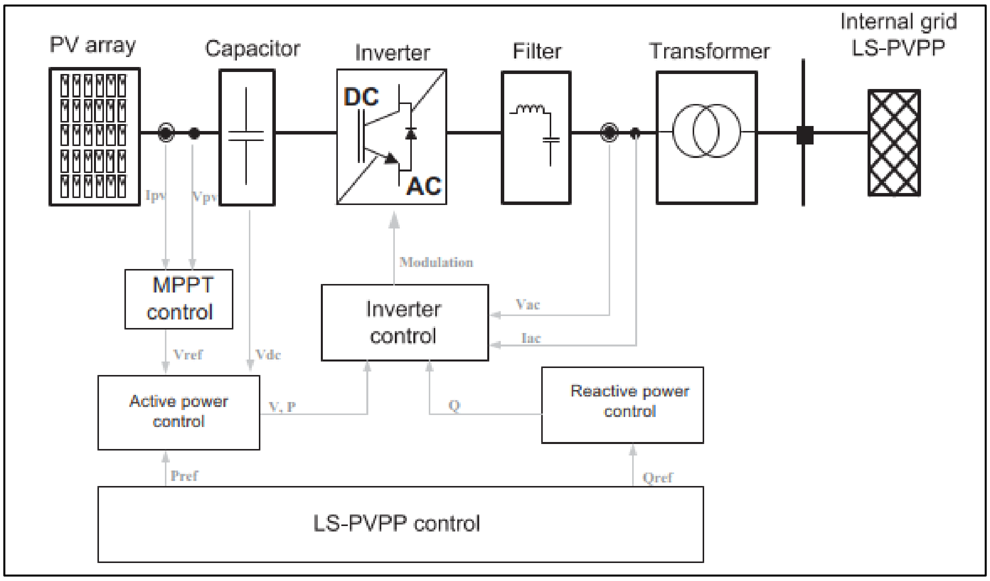

Figure 2.11: Typical Structure of a Three-Phase Grid Connected PV unit in a Utility Scale PV Plant (Ana Cabrera-Tobar, 2017)

2.3.6 SEL 3555 RTAC

A dedicated device must be configured to take on the responsibility of the PPC. A SEL 3555 RTAC (Real-Time Automation Controller) has built-in functionality supporting PPC acting. Referencing the SEL RTAC Manual on page 137, the table listed under "Communication Protocol Device Support Cout" lists the number of Modbus and IEC 61850 MMS devices that could be configured as either 'Clients' or 'Servers.' For Modbus, the total count is 256 devices of 'Clients' or 'Servers' or a combination of both. Concerning IEC 61850 MMS, the table stipulates that there can be 256 'Servers' and only 10 'Clients'. The following subsections of the Modbus and IEC 61850 protocols provide further background to the 'Client/Server' models, but for the context of the PPC, it is important to establish that since the PPC is requesting information from the PV inverters, the PPC is therefore playing the role of the 'Client.' The PV inverters respond both in information and performance according to what the PPC initiates, and thus, the PV inverters are classified as the 'Servers.'

The configuration of the SEL 3555 RTAC acting as a PPC with Modbus configuration to PV Simulation on RSCAD Fx is completed in the example provided by RTDS author Christian Jeguers. This example provides the configuration of the GTNETx2 card, the communication module for the NovaCor simulation as a Modbus server. The example also provides the configured SEL files that, once loaded to the SEL 3555 RTAC, the RTAC behave as a PPC to the simulation running on the NovaCor. This can be used as a control case for the Modbus simulation. Editing this control base to have an IEC 61850 MMS communication between the NovaCor and the SEL RTAC provides an opportunity to create a comparison study between the implementation of Modbus and IEC 61850 MMS in applying a PPC. To achieve the IEC 61850 MMS comparison, the GTNETx2 card of the NovaCor and the SEL RTAC client must be configured according to the IEC 61850 standard.

2.4 Modbus

Modbus was developed in 1979 by Modicon. (Incorporated, 2005) states that Modbus was designed for industrial automation systems running on programmable controllers. Commonly referred to as a Master-Slave protocol, Modbus uses a structure that allows a master to poll data from the slave. This is also known as a client-server protocol, where the client requests data from the server. Therefore, if a master wishes to obtain data from a particular device (slave), the master must include the slave's address.

Modbus was widely adopted, but every manufacturer created its own proprietary version of the protocol, resulting in zero compatibility between devices from different vendors.

2.4.1 Modbus Packet Frame

Concerning the Open System Information (OSI) model that describes data and data transfer using the seven-layer system. Modbus protocol is an application layer protocol as it defines rules for organizing and interpreting data as stated by (Incorporated, 2005). The message structure is, therefore, what Modbus protocol stipulates. However, the transmission medium is still required to get the data from one device to another. Two versions of Modbus emerged from the two different transmission methods used to achieve this. Firstly, Modbus RTU is referred to when Modbus protocol relies on serial communication as a physical medium connecting the two devices. Secondly, with the rise of the internet, ethernet has become a very successful method of transporting data without needing to be physically connected via a cable. The transmission control protocol (TCP) provides a structure for transferring data over a network. Thus, it gave rise to the Modbus TCP/IP protocol. Modbus RTU and Modbus TCP/IP packets can be analysed from the image below in Figure 2.12. The original message structure of Modbus is encapsulated into a TCP frame. However, the need for the checksum that is part of the Modbus RTU is irrelevant due to the nature of the TCP/IP protocol already ensuring that the data of the message is received correctly.

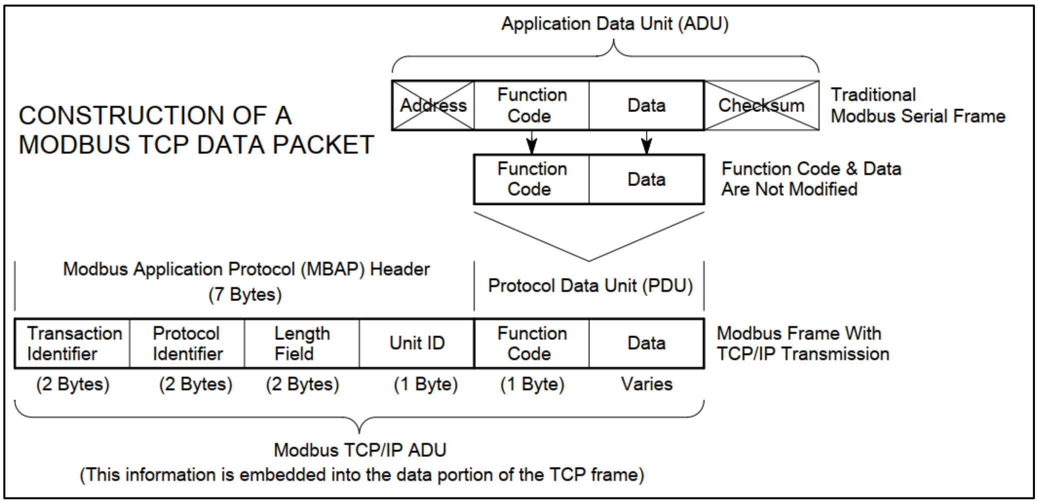

Figure 2.12: Modbus RTU and TCP/IP Frame (W. You, 2019)

2.4.2 Modbus Registers

Memory registers configure, control, and monitor devices in Modbus. Each vendor has a specific register map that details the list of signals for that device. The registers for Modbus are referred to by their function code, and primary registers are defined in the GTNET Modbus V2 Manual as Discrete Inputs, Coils, Input Registers, Holding Registers, and Exception Status. The Modbus Protocol Data Unit contains a function code corresponding to the register. For example, controlling a breaker status sends a binary state to the Coil register, which is listed in the signal list. The order of registers and their assigned function codes may vary depending on the manufacturer, as seen below in the table extracted from the RSCAD Fx GTNET Modbus manual. The GTNET Modbus manual details the working functionality of the GTNET communication module when the Modbus firmware is loaded. This is essentially the communication portal to simulation running on the NovaCor machine.

Table 2.1: Modbus Function Codes, Registers, and Data Types (RSCAD Fx GTNET Modbus Manual)

Function Code	Modbus Register		
	Description	***Read/Write***	***Data Type***
01 (0x01)	Read Coils	Read	Boolean
02 (0x02)	Read Discrete Inputs	Read	Boolean
03 (0x03)	Read Holding Registers	Read	16-bit word
04 (0x04)	Read Input Registers	Read	16-bit word
05 (0x05)	Write Single Coil	Write	Boolean
06 (0x06)	Write Single Register	Write	Boolean
07 (0x07)	Read Exception Status	Read	Boolean
15 (0x0F)	Write Multiple Coils	Write	Boolean
16 (0x10)	Write Multiple Registers	Write	16-bit word
22 (0x16)	Mask Write Register	Write	16-bit word
23 (0x17)	Read/Write Multiple Regsiters	Read/Write	16-bit word

2.4.3 Modbus Client/Server Model

As of 2024, all major inverter manufacturers (Sungrow, SMA, Huawei, etc) still use Modbus communication protocols for inverter control. This can be seen in their respective manuals for their inverters. MODBUS communication protocol was developed in 1979 and soon became the industrial control and monitoring standard. Since the protocol was open source, the development continued to be reached in many application areas. Modbus makes use of the Master/Slave relationship. The Master can also be known as the client and is the device responsible for requesting information. There is only one master or client in a Modbus network. The Slave is also known as the server and is the device responsible for providing the information requested by the master. There can be multiple servers in a Modbus network. Figure 2.13 displays the data exchange between the client and the server for the PV network.

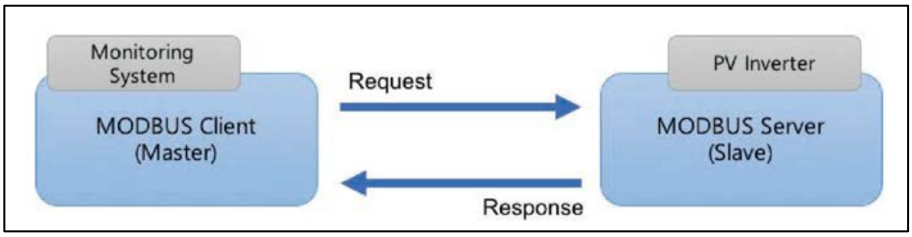

Figure 2.13: MODBUS TCP Protocol Between Monitoring System and PV Inverter (Shinyuk Kang, 2019)

A study conducted by (Thunchanok Kaewnukultorn, 2022) Displays the Hardware-In-The-Loop (HIL) configuration of using a grid emulator to monitor the grid impact of voltage stabilization using PV inverters. The simulators and power quality meter devices interact with the Control PC via GPIB Bus (IEEE-488). Two different inverters (Fronius and SMA Inverters) are connected to the Control PC via the MODBUS TCP/IP Bus. The Control PC then uses a local server to connect to a remote-control centre via the Internet. This HIL shows the Control PC providing the control and monitoring of the inverters via Modbus as displayed in Figure 2.14 below.

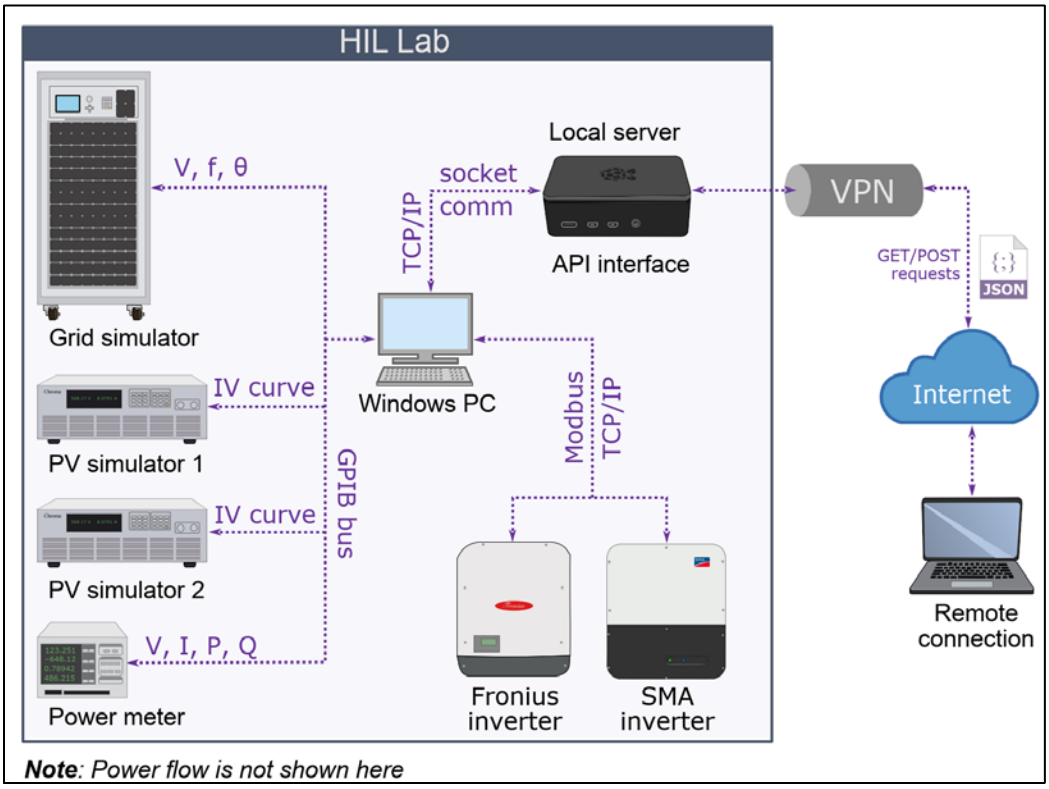

Figure 2.14: Communications Diagram of the HIL Laboratory conducted by (Thunchanok Kaewnukultorn, 2022)

2.4.4 Modbus Implementation for RTDS NovaCor Simulation

The HIL must be configured with the devices connected to create a test bed environment, as described in Chapter 3: Lab Scale Implementation. According to the RSCAD Fx manual for the GTNET Modbus V2 configuration, the implementation of the lab scale must follow the diagram below in Figure 2.15. The GTNETx2 card must be configured with the Modbus V2 firmware and connected to the NovaCor via two fiber optic ports. The GTNETx2 card is then connected to a central switch that routes traffic from peripheral devices such as the operator PC running the RSCAD Fx software and Modbus Client Stations. Modbus Client Station includes the SEL 3555 RTAC configured as the PPC.

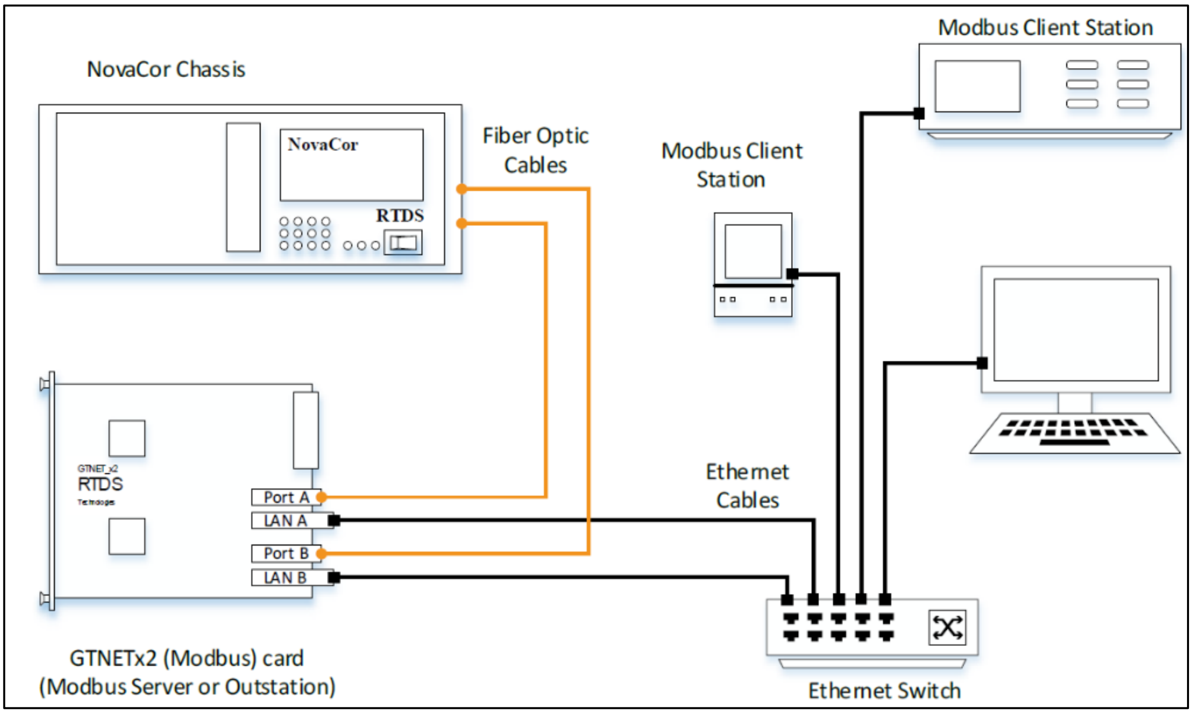

Figure 2.15: GTNETx2 Modbus Lab-Scale Implementation (RTDS GTNETx2 Modbus Manual)

MODBUS has been used for many decades across industries. However, concerning the SMART grid, a new standard, IEC 61850, has provided the format for new protocols that offer various advantages over MODBUS. The next heading focuses on IEC 61850 and compares it to the application of inverter communication in monitoring data shared with the PPC.

2.5 IEC 61850 MMS

2.5.1 IEC 61850 Overview

According to the SEL 3555 RTAC Software's Manual, the Electric Power Research Institute (EPRI) and the Institute of Electrical and Electronics Engineers, Inc (IEEE) started developing a Utility Communications Architecture (UCA) in the early 1990s. This resulted in the Inter-Control Center Communications Protocol (ICCP) specification. This specification was later adopted by the IEC as 60870-6 TASE 2. Later, in 1997, the combined efforts with the Technical Committee 57 of the IEC resulted in a common international standard known as the IEC 61850 standard. Below in Figure 2.16 is an extract from the SEL 3555 Manual that breaks down the chapters of the IEC 61850 standard for an overview.

IEC 61850 Sections	Definitions
IEC 61850-1	Introduction and overview
IEC 61850-2	Glossary
IEC 61850-3	General requirements
IEC 61850-4	System and project management
IEC 61850-5	Communication requirements
IEC 61850-6	Configuration description language for substation IEDs
IEC 61850-7-1	Basic communication structure for substations and feeder equipment- principles and models
IEC 61850-7-2	Basic communication structure for substations and feeder equipment- Abstract communication service interface (ACSI)
IEC 61850-7-3	Basic communication structure for substations and feeder equipment- Common data classes
IEC 61850-7-4	Basic communication structure for substations and feeder equipment- Compatible logical node (LN) classes and data classes
IEC 61850-8-1	SCSM-Mapping to Manufacturing Messaging Specification (MMS) (ISO/IEC 9506-1 and ISO/IEC 9506-2 over ISO/ IEC 8802-3)
IEC 61850-9-1	SCSM-Sampled values over serial multidrop point-to-point link
IEC 61850-9-2	SCSM-Sampled values over ISO/IEC 8802-3
IEC 61850-10	Conformance testing

Figure 2.16: Overview of the IEC 61850 standard (SEL 3555 RTAC Manual)

2.5.2 IEC 61850 Object-Oriented Model

The IEC 61850 standard provides an object-oriented model to which a list of protocols adheres. A significant function of the IEC 61850 standard is to ensure interoperability between different vendor devices. The standard provided a message structure for IEDs to communicate regardless of who manufactured them—a breakthrough in the SAS architecture. The SAS architecture can be seen from the extract of the IEC 61850-1-6 ‘Configuration Description Language for Substation IEDs’ below in Figure 2.17. The different levels within the SAS are listed in the figure left as station level, bay level, and process level. Within each of these levels, multiple IEDs are utilized. The IEDs at the process level interact with devices such as breakers, relays, current transformers, etc. Information regarding the equipment of the High Voltage (HV) yard is then communicated via the Process Level to the Bay Level. Bay Level IEDs communicate with the Process Level and other IEDs within the Bay Level and with station-level devices. This enables an operator to be positioned remotely and still have access to control and monitoring the entire SAS.

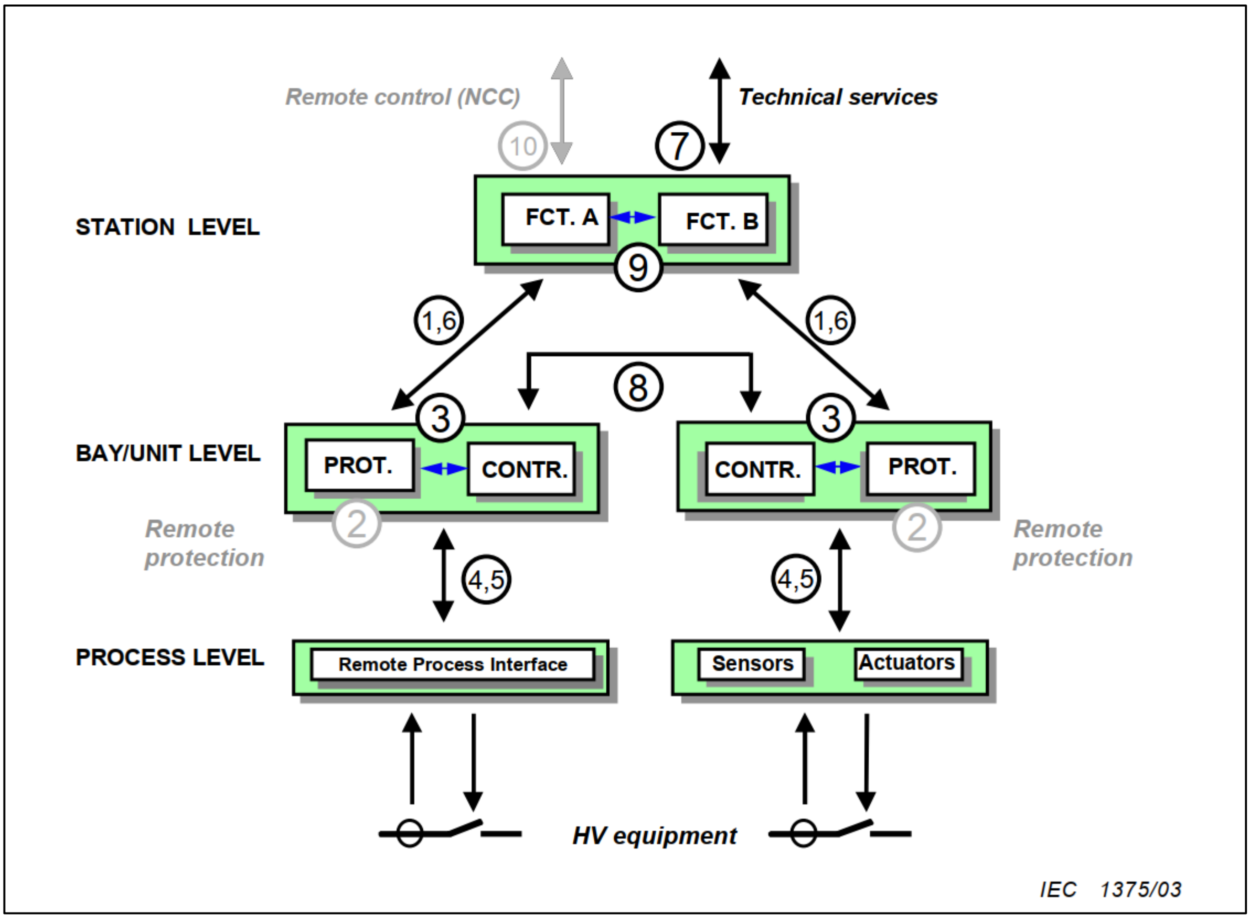

Figure 2.17: Substation Automation System Diagram (IEC 61850-1-6)

2.5.3 IEC 61850 Common Data Classes

The communication structure defined by the IEC 61850 works on a very well-established server model. The server model breaks the IED functions into Logical Nodes (LNs). These LNs include Common Logical Node Information, Status Information, Settings, Measured Values, and Controls. Within each of these LN is a list of Data Objects. Within each Data Object (DO), there is a list of Data Attributes (DA). The DA contains the actual data, whether it be the position of a breaker, a measurement of reactive power, or even the quality of established communication. Logical Nodes are then the building blocks for communication between IEDs. Figure 2.18 below shows an expanding tree diagram of a circuit breaker LN (XCBR). The DO is the position, and the DA is a list of data related to the position of the XCBR LN. It is important to note that a DA called "Operate Time" creates a time-stamped log of various changes in data. Another DA is "quality," and this provides a "valid" or "invalid" signal that states if the communication between the devices for that Data Object is achieved for any given instance. DA is defined by an attribute name (stVal for status value) and an attribute type (double point controllable – DPC).

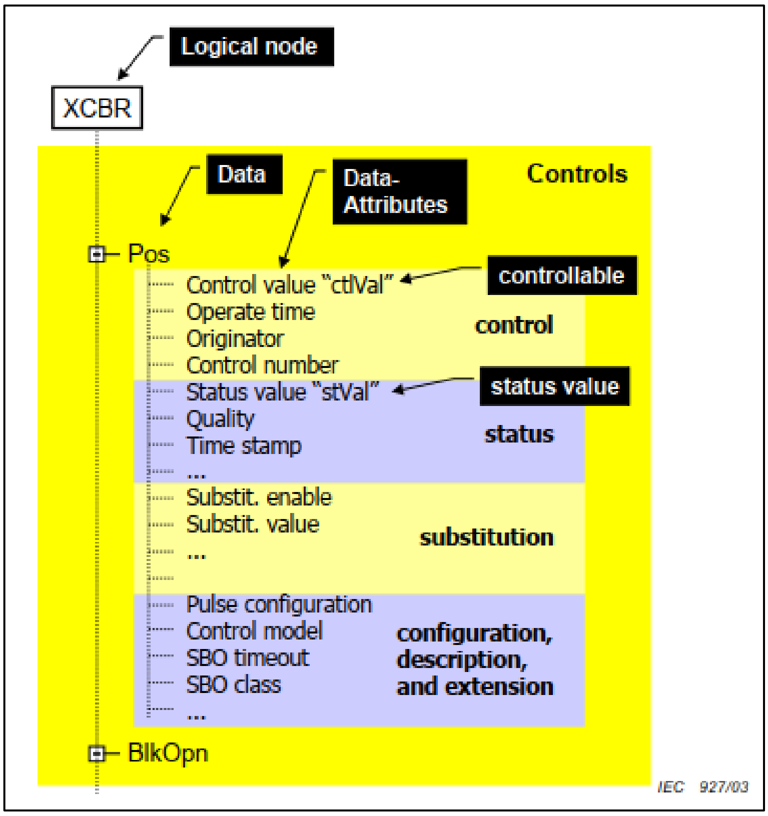

Figure 2.18: Conceptual Information regarding Circuit Breaker Logical Node (IEC 61850-7-1)

The IEC 61850 standard is divided into seven parts, each containing specific information to achieve the structure for establishing various protocols. For this research, the focus was on the Manufacturing Message Specification (MMS). The MMS protocol operates on a client-server method and is translated into a TCP/IP frame to transmit across networks.

(Apostolov, 2006) Figure 2.19 shows the object models used in the IEC 61850 standard and describes the classification of an Intelligent Electronic Device (IED) as an example. The IEC 61850 object model starts by defining the physical device and then goes into the logical nodes for that device.

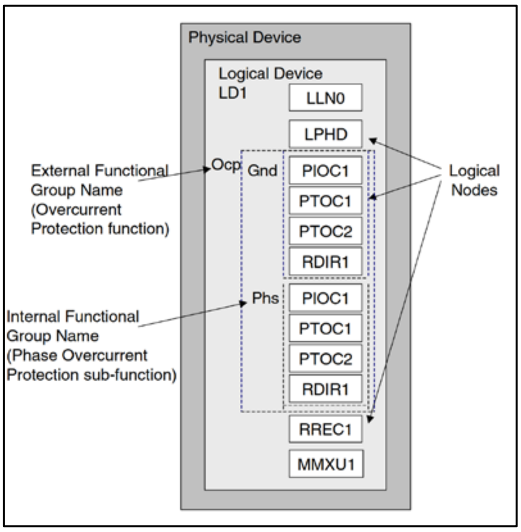

Figure 2.19: Object Model of IED as a Single Logical Device (Apostolov, 2006)

The hierarchy of accessing this information can be seen in the diagram below in Figure 2.20, extracted from (Apostolov, 2006). From this diagram the logical device is the main access gate and then the information flowchart moves from external functions, internal functions, data objects (DO) and data attributes (DA). The data attributes are considered the core fundamental elements of the communication.

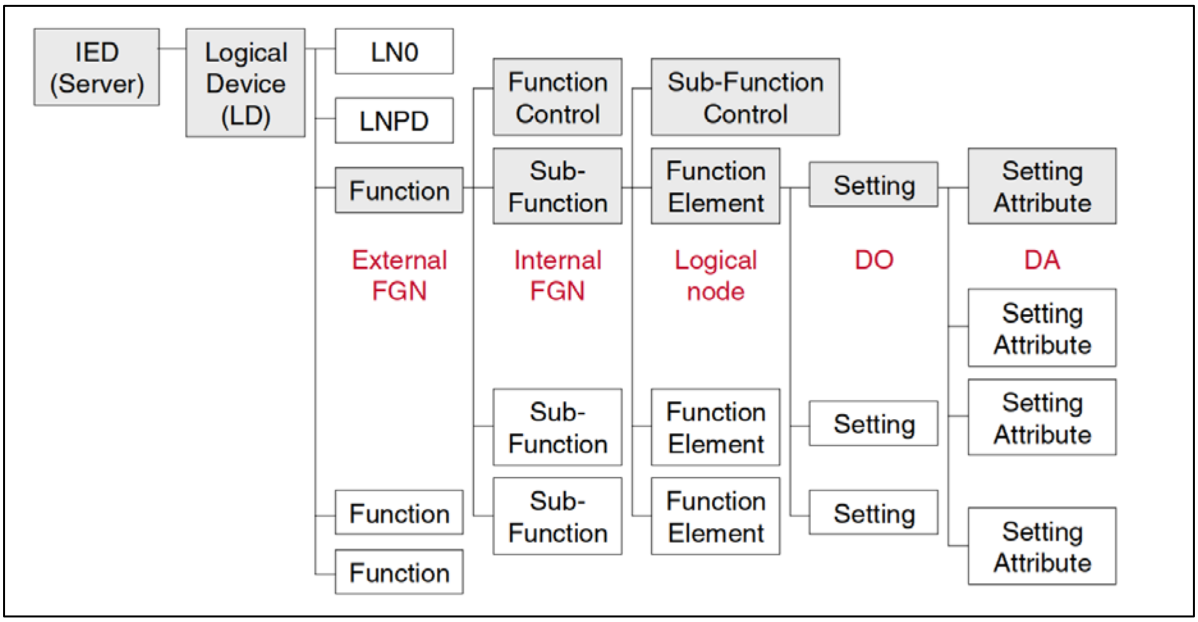

Figure 2.20: Object Hierarchy (Apostolov, 2006)

To understand how the data communication can perform in such a manner, the breakdown of the object model can be seen in code form as extracted from (Mark Adamiak, 2012) in Figure 2.21 below. As noted in the hierarchy, the logical device is kept on the left; in this case, the logical node is referenced as “XCBR,” which is translated to a switchgear circuit breaker using the IEC 61850 table. The functional constraint is denoted as “ST” and is separated from the logical node and the data through a “$” symbol. The “ST” stored as the functional constraints refers to status information. The Data object is classified as “Loc” and is the group of data attributes for this specific device. The data attribute is then denoted “stVal” and contains information about the status as addressed in the data object.

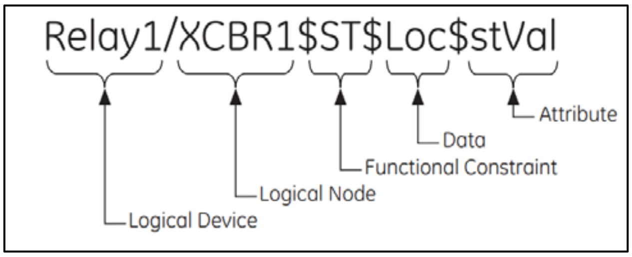

Figure 2.21: Anatomy of an IEC 61850-8-1 Object Name (Mark Adamiak, 2012)

2.5.4 IEC 61850-7-420

The successful adoption of the IEC 61850 for substation automation created further development to create a subsection around integrating the growing population of renewable energy resources. The continual growth of renewable energy penetration onto the power grid replaces the general term from bulk generation to distributed generation. This distributed generation refers to multiple nodes in the power grid that generation plants are connected to and is referred to as Distributed Energy Resources (DERs). The subsequent IEC 61850-7-420 focuses on integrating the DERs onto the power grid since the PV plant is defined as falling under the DERs using the IEC 61850-7-420 to look at the communication protocols for inverter control and monitoring.

Part of the IEC 61850 works on defining the logical nodes and creating a standard that can be used for interoperability, as mentioned above. The extract below in Figure 2.22 is taken from the IEC 61850-7-420 standard and is specific to photovoltaic integration. The legend notes that the logical node classes are in red text. It can be seen in the diagram that the DER unit controller, as the production side of the PV plant, is decoupled from the DER Electrical Connection Point (ECP) to connect the DER to the grid. Using the actual tables provided in the IEC 61850-7-420 standard, shifting from the traditional communication from MODBUS to IEC 61850 is possible.

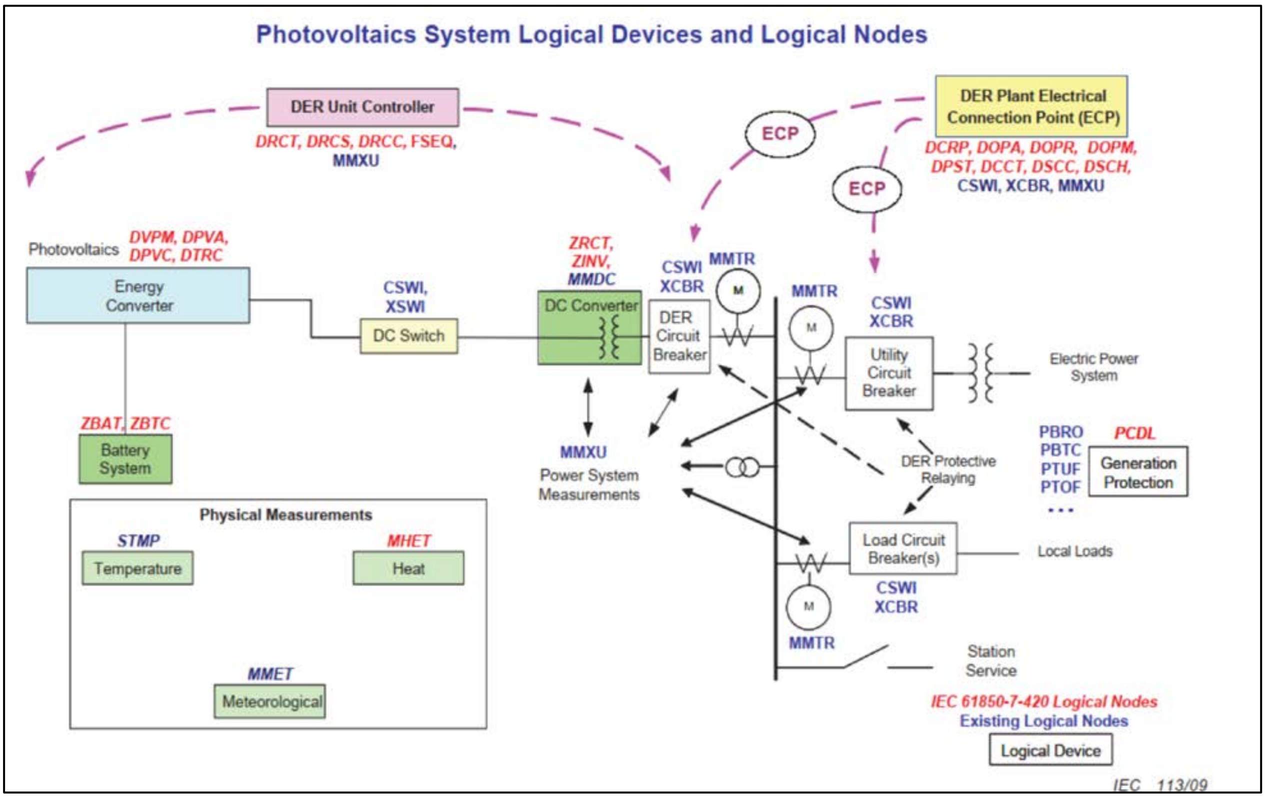

Figure 2.22: IEC 61850-7-420 Logical Nodes for PV System (Taha Selim Ustun, 2011)

2.5.5 IEC 61850 Implementation for RTDS NovaCor Simulation

Implementing IEC 61850 communications to the RTDS NovaCor requires ensuring the firmware of the GTNETx2 card has been configured with the GSEv7 firmware. This enables successful collaboration between using the GTNETx2 GSEv7 communication module in RSCAD Fx while drafting the simulation. Using the RTDS user’s manual for the ICT (IED Configurator Tool), a software used to configure the GTNETx2 GSEv7 IEC 61850 mapping. Figure 2.23 from the ICT manual guiding the updating of firmware is attached below, guiding the updating of the relevant communication module GSEv7.

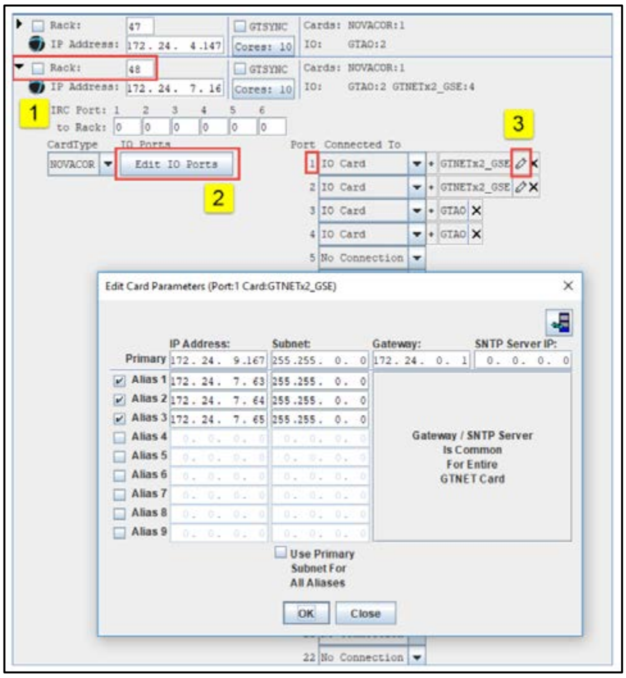

Figure 2.23: RSCAD Fx ICT User’s Manual Firmware Configuration for GTNETx2 GSEv7

Referencing the GSEv7 manual provided by RTDS as seen in Figure 2.24, the network architecture can be observed to connect all the devices coherently. This network architecture is shown in an extract from the GSEv7 manual below. A noticeable difference between the network architecture observed for the Modbus GTNETx2 application is the addition of a GPS clock providing inputs to both the GTSYNC card connected to the NovaCor RTDS and the connection of the GPS clock to external IEDs. The external IED with the connection from the GPS clock for this research is the SEL 3555 RTAC.

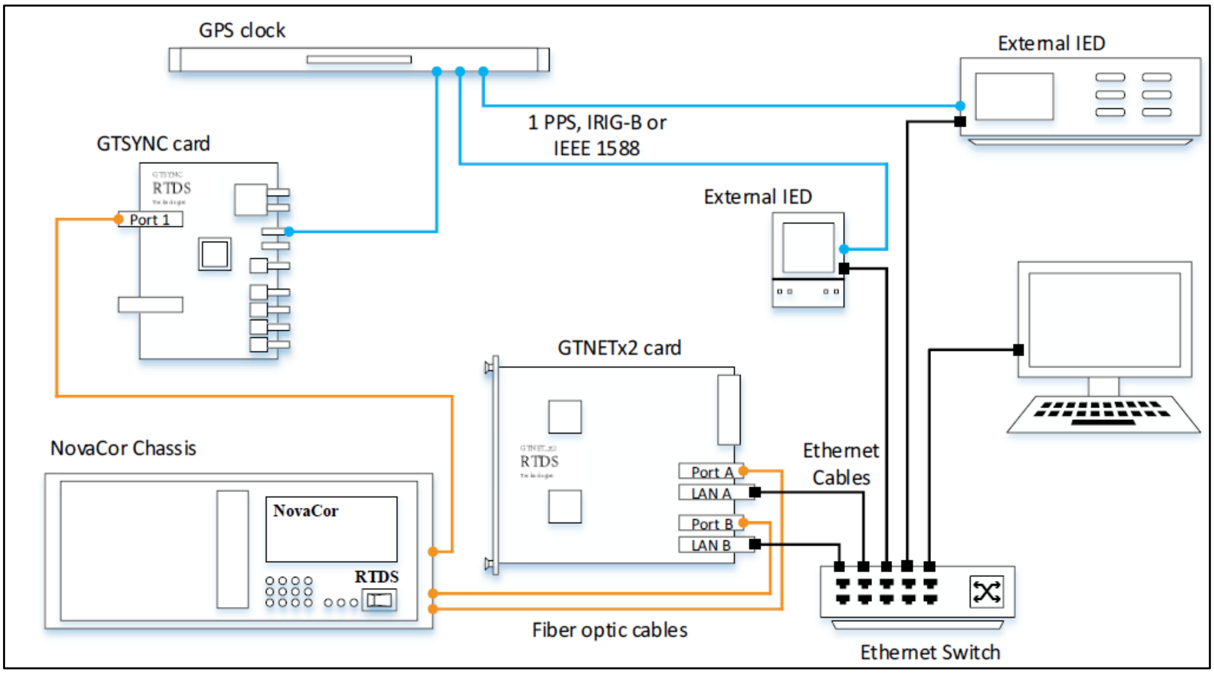

Figure 2.24: RSCAD Fx GTNETx2 GSEv7 Manual Diagram of Network Architecture (RTDS GNTETx2 GSE Manual)

2.6 Review and Conclusion

From the various chapters exploring the design and functionality of PV inverters for large utility-scale applications, it is intriguing to see their increased penetration in the generation portfolio. The energy conversion of the inverter is explored in the inverter topology, and this chapter shows a tremendous amount of research for many designs and performances. The control of the PV inverter is achieved through integrating a PPC. Communication between the PPC and the inverters must still be converted to Modbus, as none of the inverter manufacturers have implemented the IEC 61850 standard protocol. An exciting gap in the application of a widely adopted standard.

1) Inverter Topologies

The research and development of PV inverters have seen significant advancements in recent years. The VSI inverter seems to be the dominant technology utilizing multilevel-modular topology. Central-string inverters and string inverters are used in utility-scale PV systems. The constant amongst the PV inverters has been the adoption of the IGBT switching. The focus of this research highlights utility-scale grid-connected PV inverters; although there are various options, the most practical one to use on a large scale is the three-phase inverters. The PV inverter's operation creates the required functionality, such as reactive and active power, frequency control, voltage, and current control.

2) PPC

The PPC controls the PV system. It measures the PV system's output performance at the POC and interacts with the Control Operator via SCADA for setpoints. The PPC then links to the inverters and provides control and communication to optimize performance. Various algorithms have been developed to increase the effectiveness of reactive power control, and the embedded advancements have resulted in complex models that affect how the technology is implemented.

3) Reactive Power Control

The classic versus embedded reactive power control strategies are explored. It is noted that the development of inverters to provide reactive power support for the grid has improved their adaptability and ability to take up a more significant percentage of the generation portfolios.

4) Advanced Inverter Communications

Inverter communications still rely on MODBUS protocol. This is defined as the inverter manufacturers providing the specifications in the manuals, and it is noted that none of them provide the option to use the IEC 61850 standard protocols. The IEC 61850 standard is examined for its effectiveness in replacing the MODBUS protocol for inverter control and monitoring. The subsequent IEC 61850-7-420 provides the logical nodes for DER, and the data objects for PV systems are suggested as the formal communication version. The characteristics of both Modbus and MMS protocol are tabulated below in Table 2.2 for a side-by-side comparison of the information extracted from the research literature.

Table 2.2: Comparison between Modbus Protocol and IEC 61850 MMS

Aspect	Modbus Protocol	MMS Protocol
Communication Model	Master-Slave (Client-Server)	Client-Server (More dynamic, multiple clients)
Data Structure	Simple (Coils, Discrete Inputs, Holding Registers)	Complex (Object-oriented, supports rich data types)
Real-Time Performance	Moderate (Polling Mechanism)	High (Real-time communication supported)
Error Handling	Basic (CRC Checksum)	Advanced (Acknowledgments, error codes, retries)
Scalability	Limited (Fixed addressing, small payload size)	High (Scalable, extensible)
Security	Minimal (Depends on physical layer security)	Includes mechanisms for encryption, authentication
Integration	Limited (Older and modern systems may struggle to integrate)	High (supports complex, modern automation systems)
Use Cases	Simple control, monitoring, lower-cost systems	Advanced control, power plants, industrial automation

5) Summary

The summary of the research literature guides the implementation of the lab-scale work required to provide an investigation between the effectiveness of each protocol. This lab-scale work is based on the findings in the research literature and is detailed in the following Chapter 3.

Chapter 3: Lab-Scale Implementation

This chapter provides a detailed explanation of the lab-scale implementation completed at Cape Peninsula University of Technology (CPUT) Centre for Substation Automation and Energy Management Systems (CSAEMS). Concerning the literature and manuals provided in Chapter 2, the successful compilation of the simulations is achieved. It has already been established that an example case from RTDS can be used for the simulation running on Modbus communication between the NovaCor and the SEL 3555 RTAC (PPC). This example must be configured into the local network and compiled successfully to get packets detailing the data transmitted in the Modbus protocol. However, before establishing the necessities that provide a compilation with the Modbus protocol, the example detailed below in Chapter 3.1 should be held constant between both simulations. The following subsections, 3.2 for Modbus Protocol and 3.3 for IEC 61850 MMS protocol provide the detailed configuration that produces unique communication between the simulation running on the RTDS NovaCor and the SEL 3555 RTAC acting as the PPC. The purpose of this lab-scale implementation is to capture the data transmitted between the devices so that a comparative study of the effectiveness of each protocol is investigated. It is noted that the extent of this research only focuses on the implementation of the protocols for monitoring purposes. The theory of control for each protocol is still discussed in the research literature as it provides fundamental parts of each protocol and can be used in comparing the protocols.

In summary, the lab-scale implementation successfully compiles two simulations of the PPC communicating with a simulated PV system. The iteration for the simulation allows the second configuration to implement the newly proposed IEC 61850 protocol in replacement of the Modbus configuration seen in the first simulation. The PV systems remain identical in both simulations, and the configuration of the communication modules is adjusted to each protocol. This allows the data captured and analysed to be comparable and the functionality of each protocol examined. The simulations are compiled on RSCAD Fx software and simulated on the RTDS NovaCor machines.

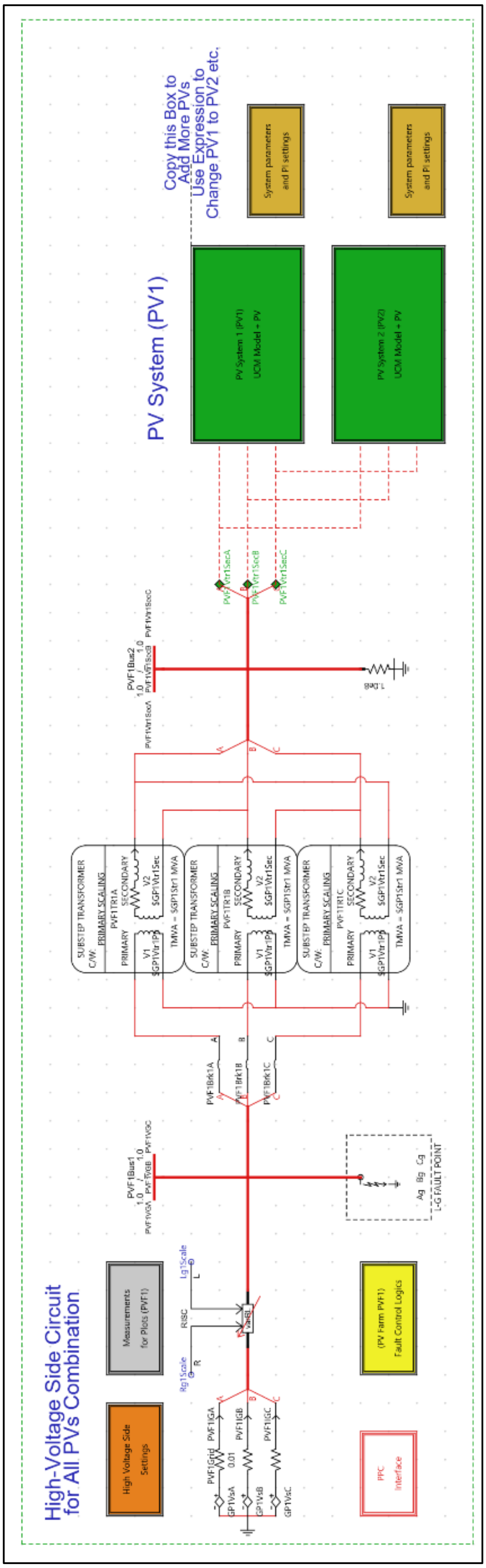

Figure 3.1 PV System Model on RSCAD Fx

3.1 PV PPC modelling in the power system simulation tool

The simulation of the PV system with the SEL 3555 RTAC is loaded from the RTDS library for examples of renewable plants. Credit goes to the original author, Christian Jeguers, for providing the composed simulation that established an HIL simulation in which a SEL 3555 RTAC is configured as a PPC and communicated with the PV system simulation running on the RTDS NovaCor. Various steps are still required to complete the simulation on the local area network (LAN) at the CPUT lab. A step-by-step approach is provided to show the details of the example and configuration of the LAN. The primary focus is on establishing the communication modules configured to Modbus protocol.

3.1.1 RSCAD Fx Draft Case:

Loading the RSCAD Fx project file is achieved by opening the PPC_PVPowerPlant_SELRTAC_R01 RSCAD FX File provided by the RTDS library. The draft case shows an overview of the two PV systems connected to an HV transformer before connecting to a busbar and a variable load consisting of a resistance and inductance that enables the simulation of the grid. The two PV systems are placed inside the green hierarchy boxes on the far right of the draft case. The orange hierarchy boxes labelled 'System parameters and PI settings' provide logic for controlling the PV inverters connecting the grid. Furthermore, additional hierarchy boxes are used for the high voltage side settings, measurement for plots, PPC interface, and PV Farm PVF1 Fault Control Logics. It is essential to understand the compilation of the draft to extract meaningful data once the simulation runs accurately. These hierarchy boxes can be seen in Figure 3.1 below. Modifying the correct components to keep the control variable in the experiment constant with the variation under investigation focused on the communication data is equally important. Therefore, the PPC Interface is the only hierarchy box that can be modified. However, certain hierarchy boxes are examined to provide an understanding of the compilation of this simulation. The PV System 1 hierarchy box extract has already been studied in Chapter 2.1.6 Figure 2.8. The provided manual for operating the example explains that the PV systems attached in the simulation are scaled to produce power at a different scale. This scaling results in PV System 1 producing a maximum output of 1 MVA, and the production of PV System 2 is 2 MVA. This simulates two separate PV systems being controlled by a single PPC.

3.1.2 RSCAD Fx Draft Case – Hierarchy Boxes:

For the lab-scale implementation, it is essential to understand the start-up control logic required to close the breakers so that the PV inverters can inject power into the grid. The start-up logic for PV system one is examined below in Figure 3.2. Starting in the top left corner of the draft window are two push buttons for 'PV1DBlkLocal' and 'PV1BlkLocal'. The 'DBlk' refers to unblocking the breaker so that it operates, and the 'Blk' function is to reset the breaker to its initial position. Below the push buttons are toggle switches for 'PV1LocalOrPPC'; one toggle switch is focused on 'DBlk' whereas the second toggle switch is focused on ' 'Blk.' Each toggle switch provides an option between the 'DBlk' or 'Blk' function to be controlled remotely (via the PPC) or locally (via the Runtime simulation). In the middle of the draft window, it shows 'AND' Boolean logic for 'MainBrk' and 'PV1DBlk'; provided both these conditions are true, the Set-reset flip flop function block is triggered. This is triggered on the rising edge of the 'AND' function, resulting in a signal called 'PV1DBlk1'. This signal then uses another 'AND' logic to deblock breaker 2 called 'PV1DBlk2 automatically'

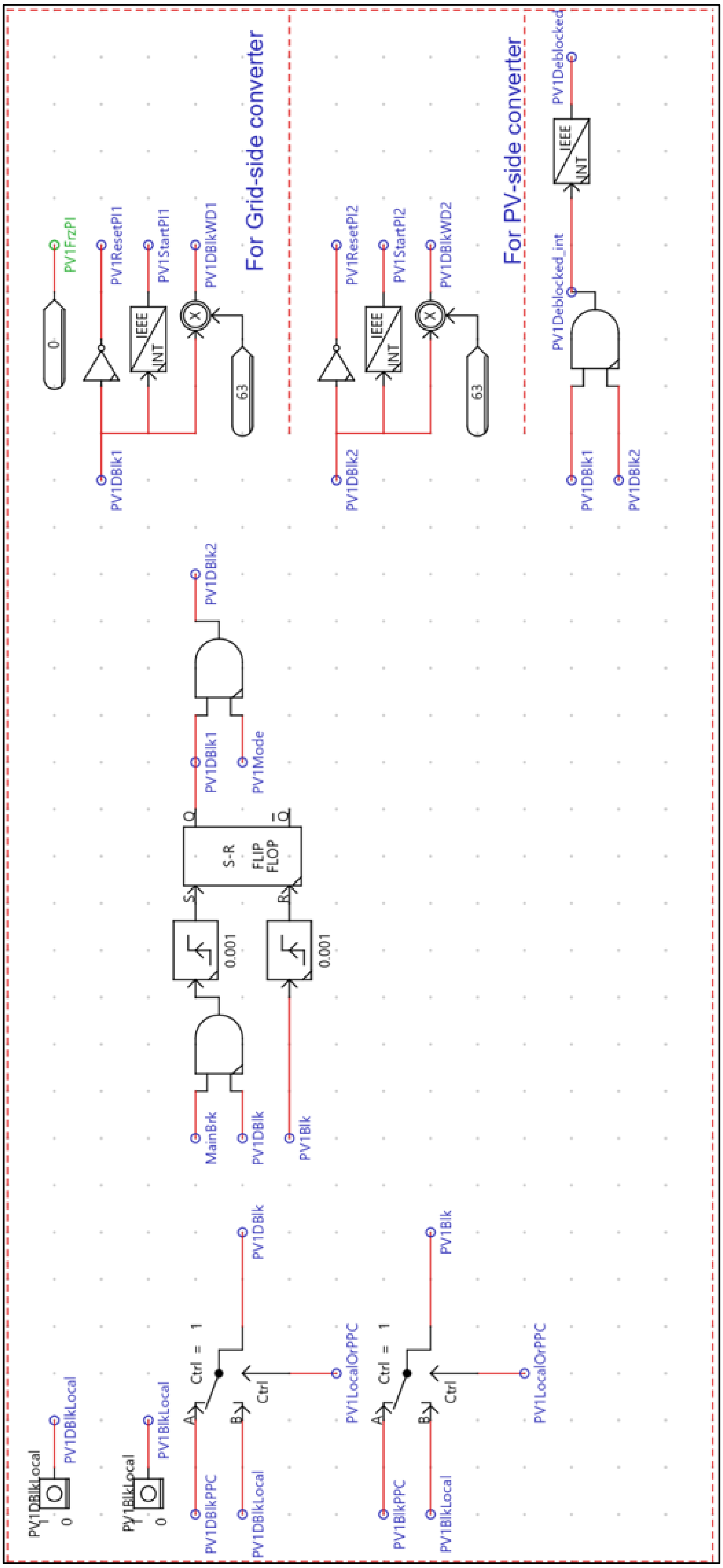

Figure 3.2: PV System 1 – Start-up Logic

There are two methods of operation for the simulation to close the PV inverter breakers to allow them to produce power onto the grid. The two options are seen as ‘Local’ or ‘PPC’. The decision between using the RSCAD FX simulation to operate the breakers in ‘Local’ mode or the SEL 3555 RTAC to operate the breakers in ‘PPC’ mode must be determined initially. Operating the breakers in ‘Local’ mode requires buttons and sliders provided by RSCAD FX to actuate the control. This is detailed in the RSCAD Runtime window and is still to follow. The ‘PPC’ mode requires the operator to log into the SEL 3555 RTAC and send commands from the PPC. The status of the breakers should always be communicated via monitoring the signals. Following the control logic provided for the ‘PPC’ control, the signal ‘PV1DBlkPPC’ deblocks the PV system one breaker one and allows the close command to be accepted. The respective deblock signal in the ‘Local’ mode is ‘PV1DBlklocal’. Once the simulation has received either of these signals, the logic follows that a signal named ‘PV1DBlk’ will be produced. This signal is then used as an input along with the ‘MainBrk’ signal to initiate the ‘PV1DBlk2’ signal. These two signals, ‘PV1DBlk’ and ‘PV1DBlk2’, are used in Boolean logic as an ‘and’ function to produce the output ‘PV1Deblocked’ signal. In reviewing this control logic provided for PV System 1, two breakers are required to close the PV inverters onto the grid, and they require a deblocked function before operating. There is also an additional breaker called ‘MainBrk’ that is separate from the PV System and is a priority for closing PV System 1 for producing power. For this research, the signal names for the breakers are essential to register as they are used in the communication mapping, which is still to be defined.

A similar investigation looks at the Start-Up logic for PV System 2. Concerning Figure 3.3 below, it is noted that the same logic is applied for PV system 2. However, although the same start-up logic is used, there is a difference in the denotation of the signal names. Signs relating to PV system 1 begin with ‘PV1’, and signals relating to PV system 2 begin with ‘PV2’. The signal ‘MainBrk’ is independent of either PV system as it connects both PV systems to the grid.

Following the logic displayed in Figure 3.3, the output of the ‘PV1DBlk1’ and ‘PV2DBlk1’ produces a cascading effect for generating other signals. This is seen as the input to the ‘AND’ logic in the center of the window requires both the ‘MainBrk’ and the ‘PV1DBlk’ or ‘PV2Dblk’ for PV System 2 to be true. The output of the flip flop function block generates a ‘DBlk’ function for the first circuit breaker in the PV systems. This PV1DBlk1 or PV2DBlk1 then results in the PV1DBlk2 or PV2DBlk2 to be triggered. These signals all influence the output of the PV systems, as seen by the ‘OR GATE’ logic and the ‘Integer to decimal’ conversion function block. These output signals are relevant for the initialization of the grid side converter and PV side converter.

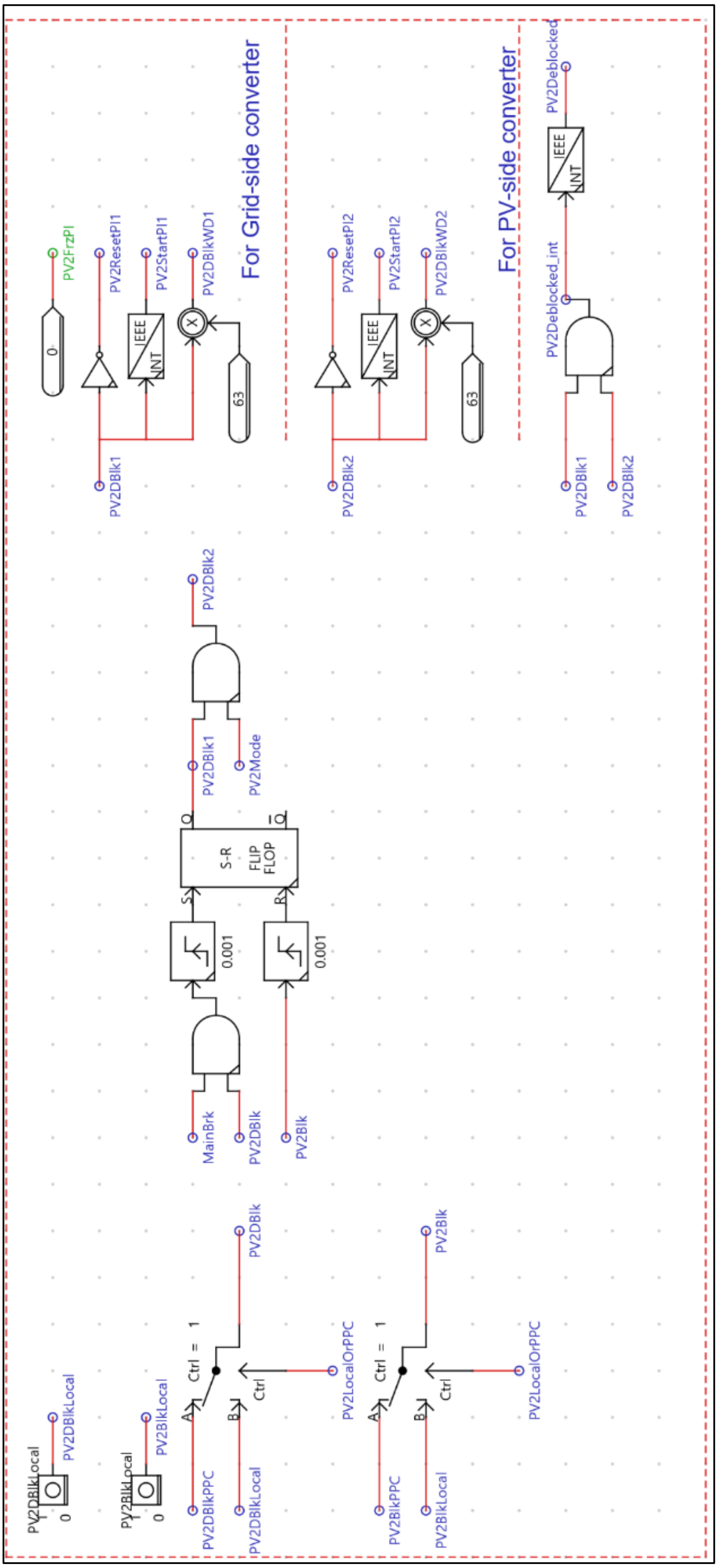

Figure 3.3: PV System 2 – Start-up Logic

Concerning Figure 3.1: PPC_PVPowerPlant_SELRTAC_R01, another hierarchy box that is important to note is the 'Measurement for Plots', which is shown below in Figure 3.4. Concerning the signals displayed in the Measurement for Plots hierarchy, a three-phase meter for reactive and active power has been used to interpret the voltage and current outputs. The measurement of the signal's logic is explained further. The output of this three-phase meter uses a 'gain function block' to provide filtered values for the active and reactive power readings produced from the combined PV systems performance. These values are provided by signal names 'PVF1PGfil' for the active power and 'PVF1QGfil' for the reactive power. The input to the Three-Phase meter on the left-hand side is based on Voltage as seen in the notation of the signals PVF1VGA, PVF1VGB, and PVF1VGC for a three-phase voltage system A, B, and C. The second three-phase meter is similar but uses current inputs instead of voltage inputs. A list of signal names noted as PVF1ItrSecPhA, PVF1ItrSecPhB, and PVF1ItrSecPhC are determined by combining an addition and subtraction logic of other phase currents. This 'PVF1I' annotation refers to the current output phases A, B, and C measured at the transformer (noted 'tr'). A special focus is also placed on the 'Per Unitization' signals. Both the previous signals, 'PVF1PGfil' and 'PVF1QGfil', are exposed to open-loop control to provide a per unit signal referred to as 'PVF1PGPUfil' and 'PVF1QGPUfil', respectively. The open-loop control circuit can calculate the power factor denoted as 'PVF1PF' using these per-unit signals for active and reactive power. The inverters can match the frequency and voltage level of the grid using a 'PLL Control Block' with the inputs configured as the voltage from the combined PV systems and the base frequency matched to the grid frequency. The output is noted by the signal name 'PVF1fGPPL1filt' for the phase-lock loop; the importance of this has been described in Chapter 2.1 and is related to controlling the output of the PV system to be synchronized with that of the grid.

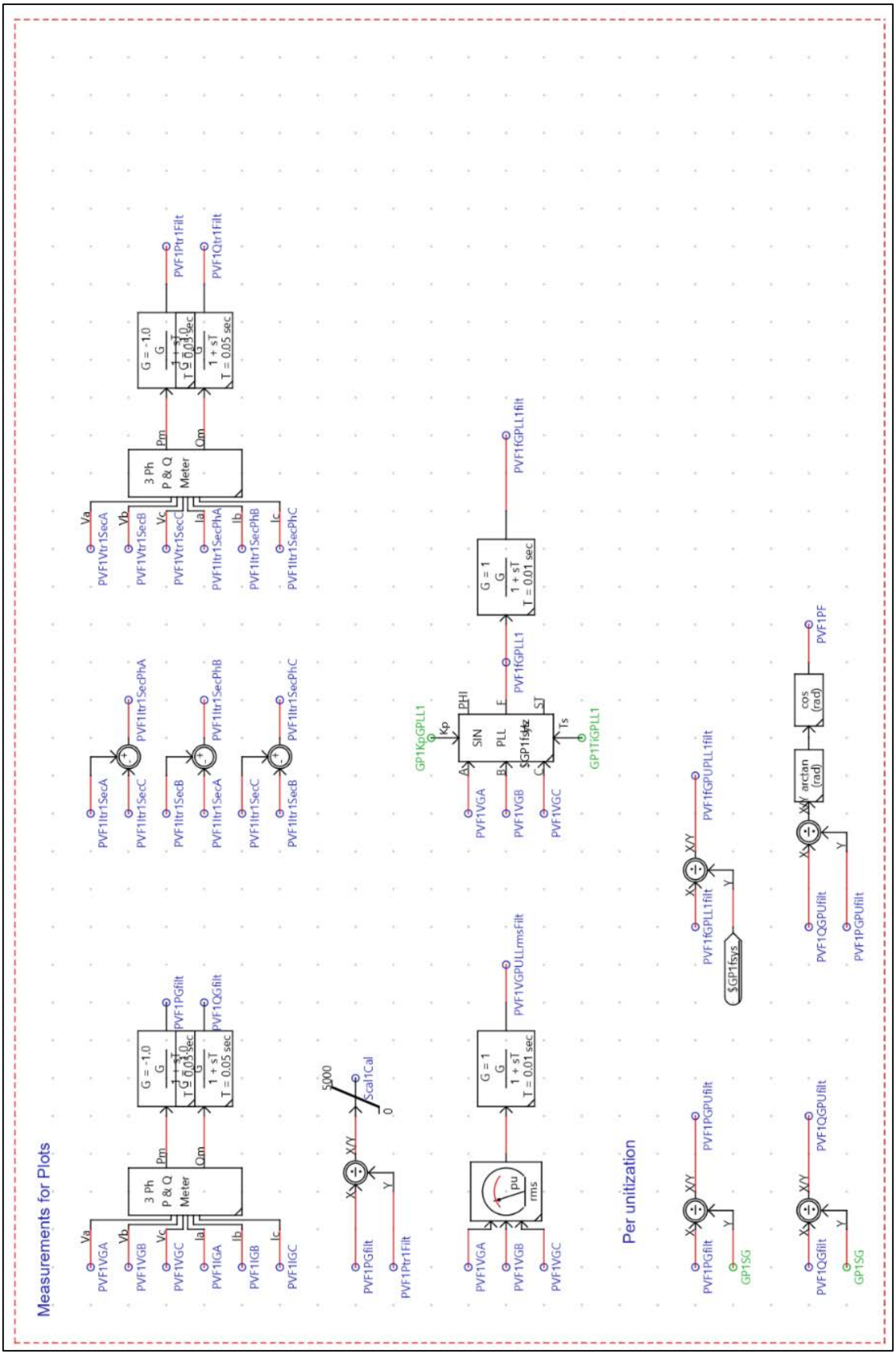

Figure 3.4: RSCAD FX Measurement for Plots

3.1.3 RSCAD Fx Runtime View:

The configuration of the RSCAD Fx draft components previously seen in the chapter above is linked to plots and graphical user interfaces (GUIs) in the RSCAD Runtime window. The RSCAD Runtime is a separate project file used to interact with the draft case that is loaded for real-time simulation on the RTDS NovaCor. The Runtime window, therefore, displays essential information regarding the simulation and can be used to interact with the simulation. Using the Runtime GUIs to interact with the simulation is considered 'Local' control. The status of breakers can be viewed and easily interpreted via indication lights. The green indication represents that the breakers are open, and the red indication light indicates the breakers are closed and the PV system is live. Additional plots are provided for a detailed view of the waveforms and per-unit signal plots. The Runtime window for the initial state before any simulation can be seen in Appendix A: RSCAD FX Runtime Initial State.

3.2 Modbus Protocol Simulation

The previous section focused on components of the simulation that remain constant between the compilation of the two different case scenarios, Modbus and IEC 61850 MMS. This section focuses on the detailed configuration of the simulation, which is specifically designed for successful communication between RTDS NovaCor and SEL 3555 RTAC using the Modbus protocol.

3.2.1 Lab-Scale Setup for Modbus Simulation:

The RSCAD Fx simulation requires that the communication module GTNETx2 card is loaded with the latest Modbus V2 firmware. Therefore, the appropriate LAN configuration must follow the LAN configuration discussed in Chapter 2.3 Figure 2.14. Concerning that diagram, a list of IP addresses is provided for the devices connected to the lab. These IP addresses can be referenced below in Table 3.1

Table 3.1: Modbus Protocol Simulation – IP Addresses

Item	Device Description	IP Address
1	RTDS NovaCor	192.168.1.105
2	GTNETx2 Modbus	192.168.1.205
3	SEL 3555 RTAC (PPC)	192.168.1.170
4	Operator PC	192.168.1.199
5	Ethernet Switch	192.168.1.15

3.2.2 Modbus RSCAD FX Draft PPC Interface Hierarchy:

The draft case, as examined in the previous subsection, contains multiple hierarchy boxes. These hierarchy boxes are extensions to the draft case and are categorized accordingly. The hierarchy box containing the Modbus communication configuration is placed within the 'PPC Interface' box. This section examines the configuration and establishes a successful configuration for the LAN available at the lab. Below is an extract from the PPC Interface hierarchy. Noting the Modbus Register Table 2.1 in Chapter 2.2. The signal list is mapped in a draft case before configuring the GTNETx2 Modbus V2 component. Discrete Inputs and Coils are listed straight as inputs from the RSCAD draft. They include the signals for monitoring and controlling the breakers for each PV system and the 'MainBrk'. The Input

Registers required using the 'Float to Binary' function block to transmit the data from the simulation into two 16-bit registers that are interpreted as a 32-bit floating point. These signals include the per-unit data examined in the previous subsection and represent the active power, reactive power, and grid voltage levels. The Holding Registers have a reversed function block to that seen in the Input Register because the signals coming into the simulation from the Modbus need to be converted from Binary to Float, hence the 'Binary to Float' function block. The two 16-bit registers are seen as inputs to each function block, and the outputs computed by the simulation are the active and reactive power per unit setpoints for each PV system. It is clearly labelled in the draft case demonstrating which signals are coming from the PPC and which signals are going to the PPC.

A summary of Modbus registers with respect to the signal lists is provided below and shown in Figure 3.5 below.

Discrete Input

Discrete inputs are single-bit registers with either 0 or 1 binary states. They only have read functionality attached to them. In the context of the signal names listed under discrete inputs, it is stated that the breaker status for 'MainBrk', 'PV1DBlk1', 'PV1DBlk2', 'PV2DBlk1' and 'PV2DBlk2' are to be read in terms of open or closed.

Input Registers

Input registers are data that can be 16-bit integer or float. For RSCAD Fx, the requirement to use a float-to-integer conversion function block is met in the RSCAD Fx draft. Input registers are also limited to read functionality. Therefore, the data provided in the signal names 'PVF1PGPUfilt', 'PVF1QGPUfilt', and 'PVF1VGPULLrmsfilt' are divided into two separate signals, each as the data is 32-bit long. Respective 16-bit signal names are 'PVF1PGPUfilt_0-15' and 'PVF1PGPUfilt_16-31'.

Coils

Coils are single-bit Boolean data like the Discrete Inputs, except that Coils have read and write functionality. Therefore, a command could be sent to change the status. For this research project, the investigation is limited to monitoring purposes.

Holding Registers

Holding registers are like Input Registers but with additional control functionality, such as being read and write capable. As mentioned with Coil registers, this research project is focused on monitoring for its investigation.

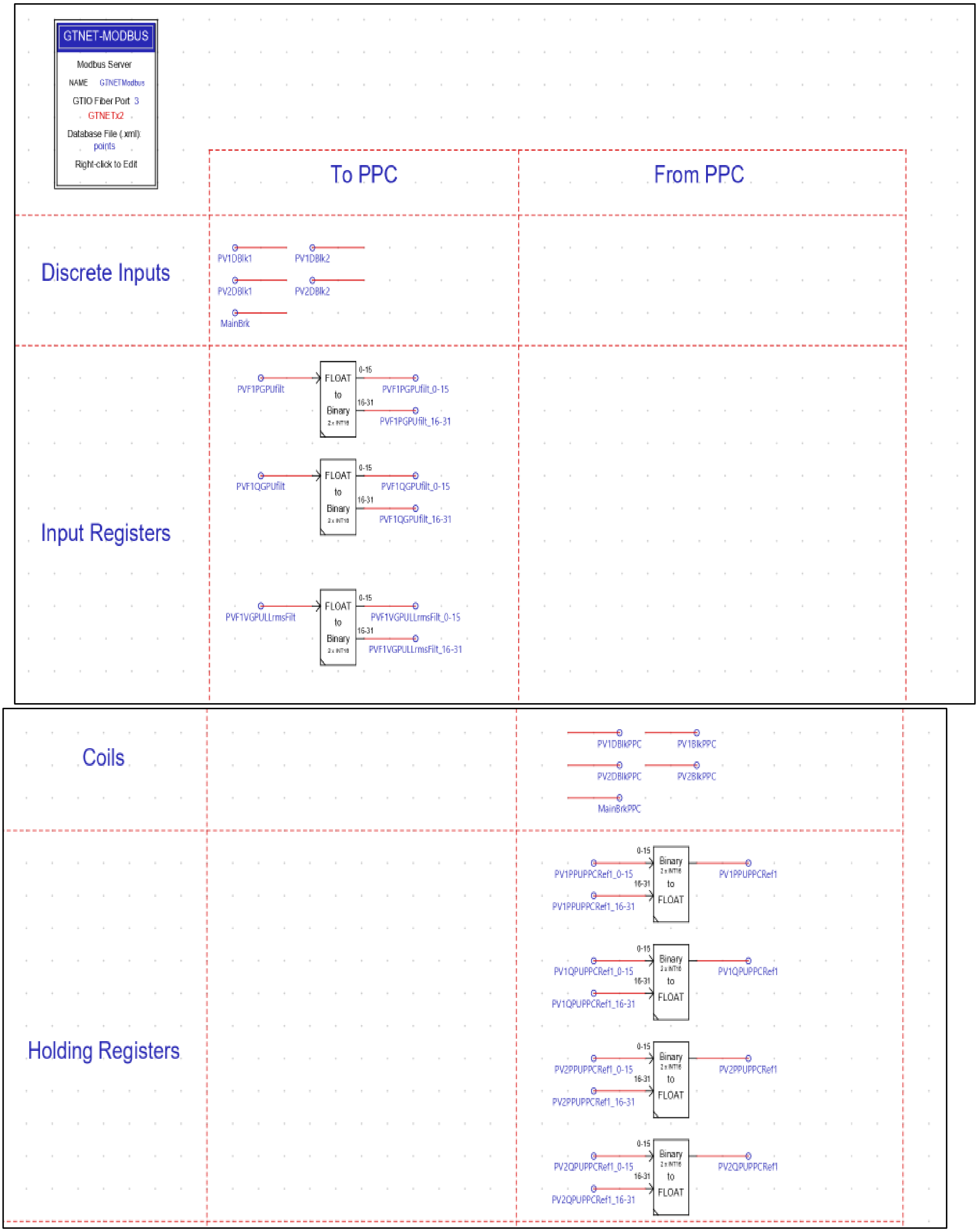

Figure 3.5: RSCAD Fx PPC_PVPowerPlantController_SELRTAC PPC Interface

3.2.4 GTNETx2 Modbus V2 Configuration:

The GTNETx2 Modbus v2 component configures the Modbus communication module that interacts with the GTNETx2 card connected to the RTDS NovaCor. Therefore, it is essential to configure the GTNETx2 component according to the current setup in the lab. This involves editing the component name to ‘GTNETModbus’ and the fiber port to 3, as seen in Figure 3.6 below. The reason for the fiber port being selected as ‘3’ can be covered in the following subsection in the RSCAD Fx configuration.

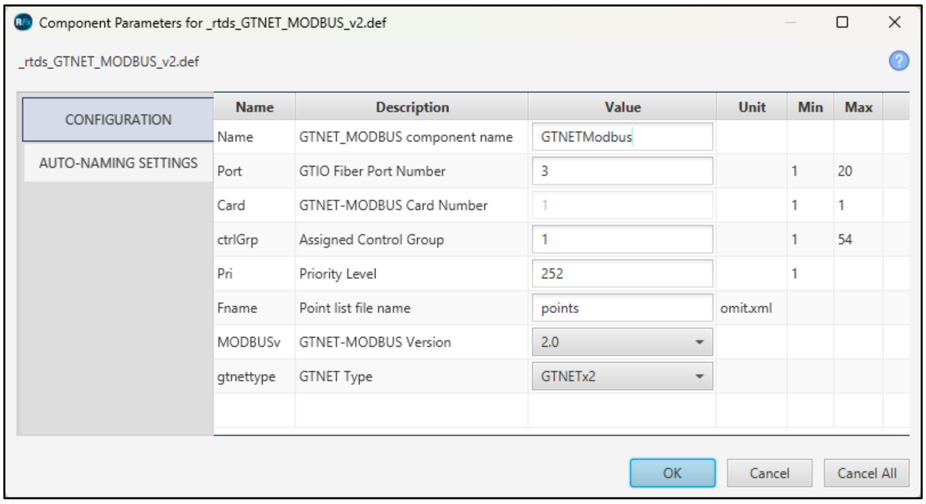

Figure 3.6: RSCAD FX GTNETx2 Modbus v2 Configuration

After the GTNETx2 component has been configured, the actual signal mapping is done using the plugin software ‘MODBUS Database File’. Detailed instructions on accessing the plugin software are provided in the GTNETx2 User Manual supplied by RTDS. An extract of the Modbus Database File software is provided below, showing the mapping to each function code register required for Modbus communication. These are mapped to the same registers as seen in the draft case above in chapter 3.2.3. However, the ‘Outstation’ tab displayed in Figure 3.7 requires configuring the outstation name, remote IP address, and GTNET TCP/UDP Port number. The outstation name is ‘IED1’, and the remote IP address is 192.168.1.170 (SEL 3555 RTAC). The GTNET TCP/UDP port is set to 502, as this is designated for Modbus devices to send and receive data. Figure 3.8 shows the signal mapping for the Discrete Inputs. Figure 3.9 shows the signal mapping for Input Registers. Figure 3.10 shows the Discrete Registers. Figure 3.11 shows the signal mapping for the Holding Registers. These figures conclude the signal mapping for the Modbus registers used to communicate data exchange between the RTDS simulation of the PV plant to the PPC.

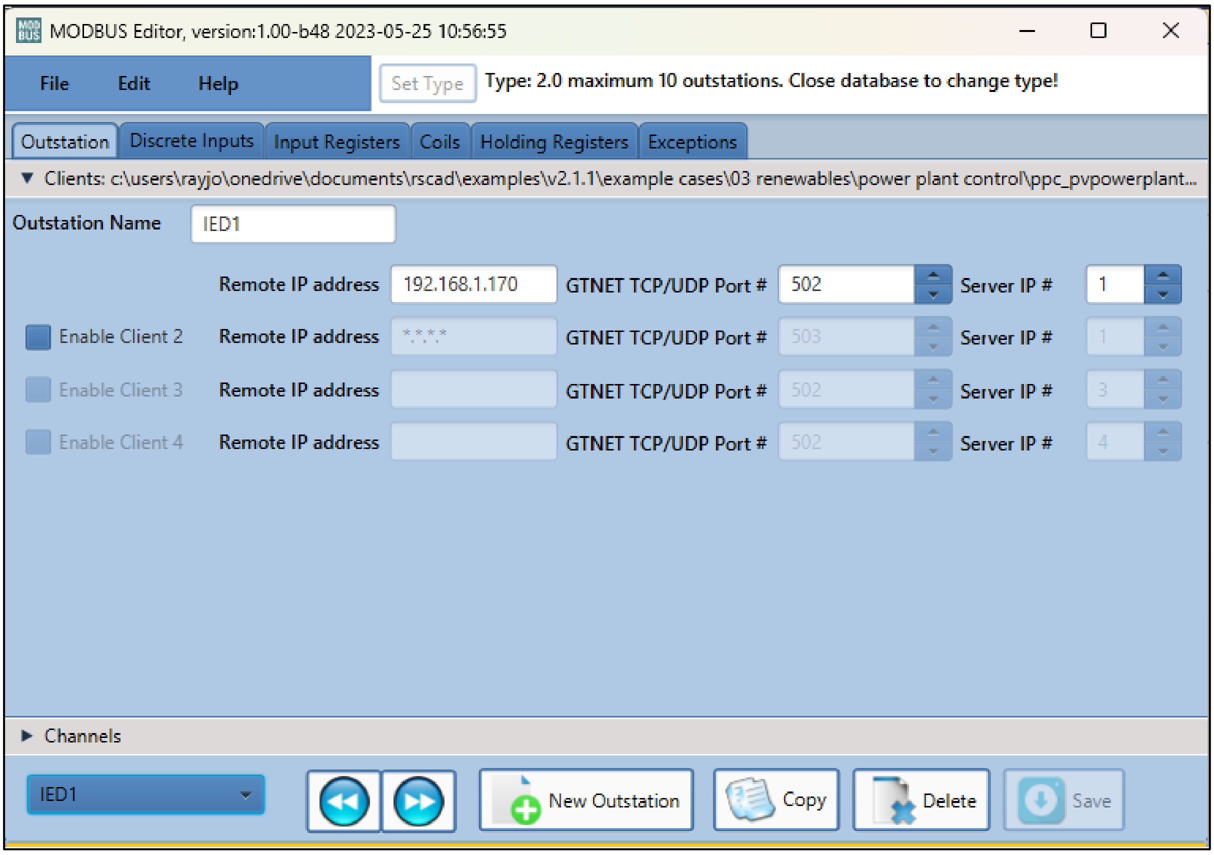

Figure 3.7: RSCAD FX Modbus Database File – Outstation

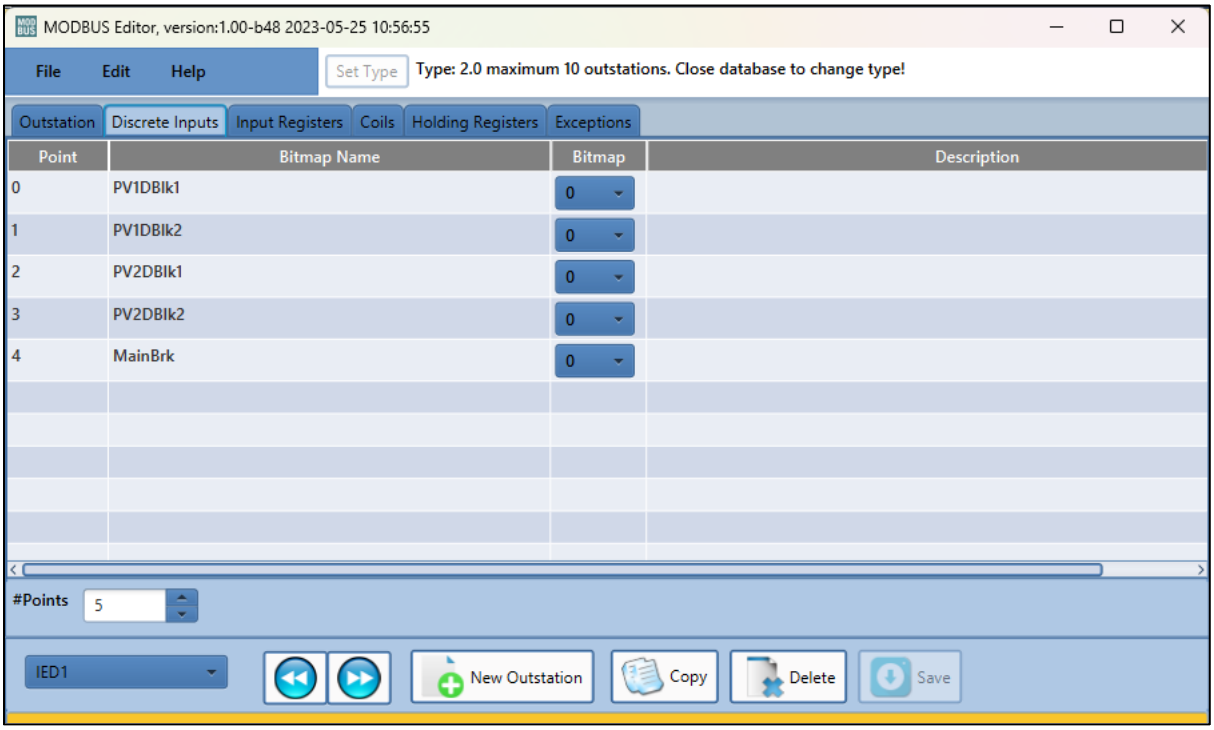

Figure 3.8: RSCAD FX Modbus Database File – Discrete Inputs

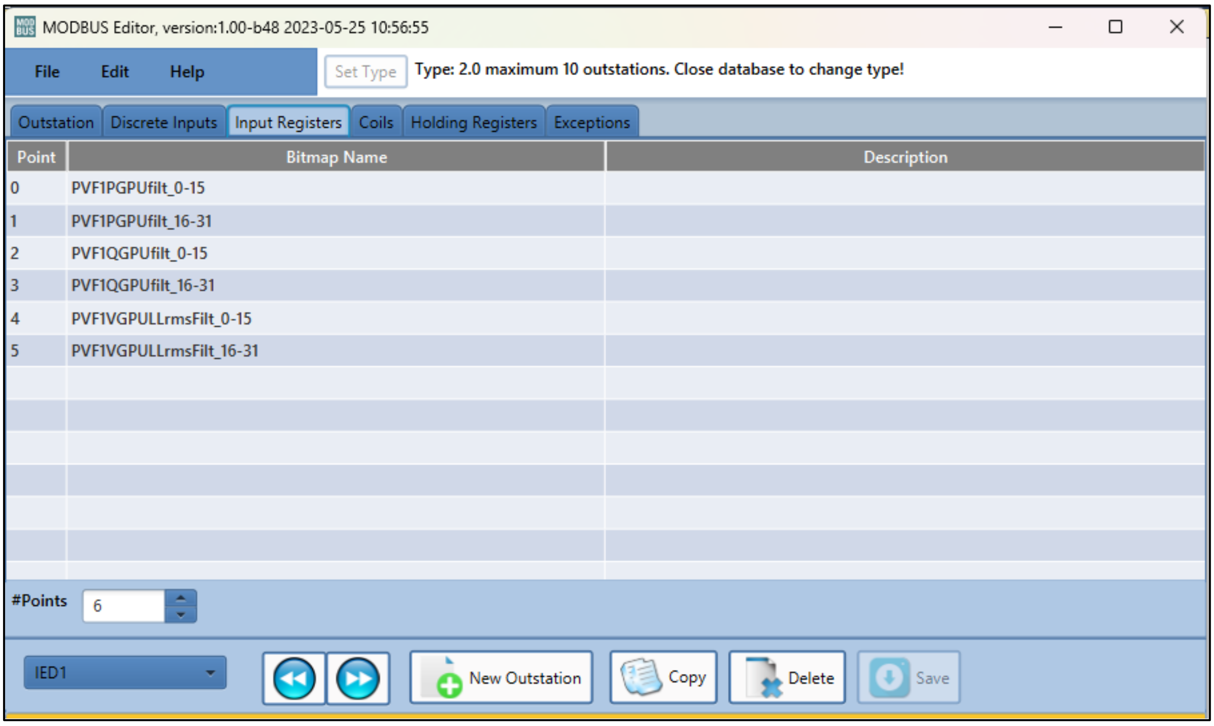

Figure 3.9: RSCAD FX Modbus Database File – Input Registers

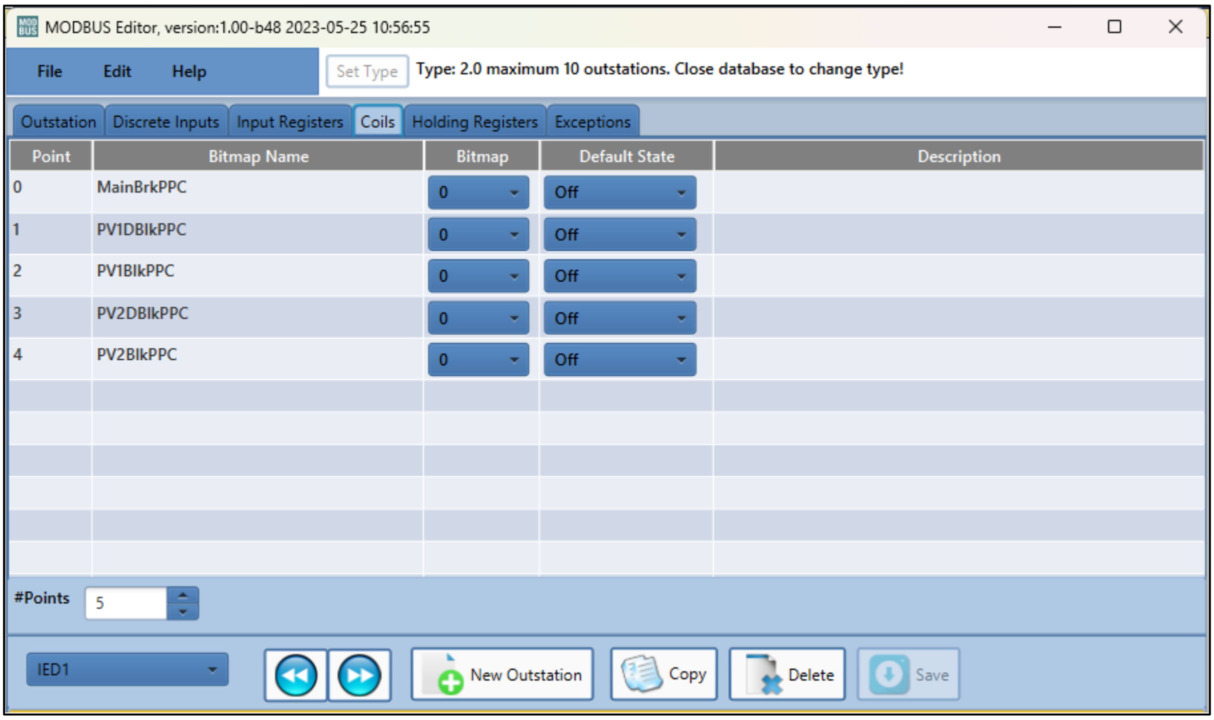

Figure 3.10: RSCAD FX Modbus Database File – Coils

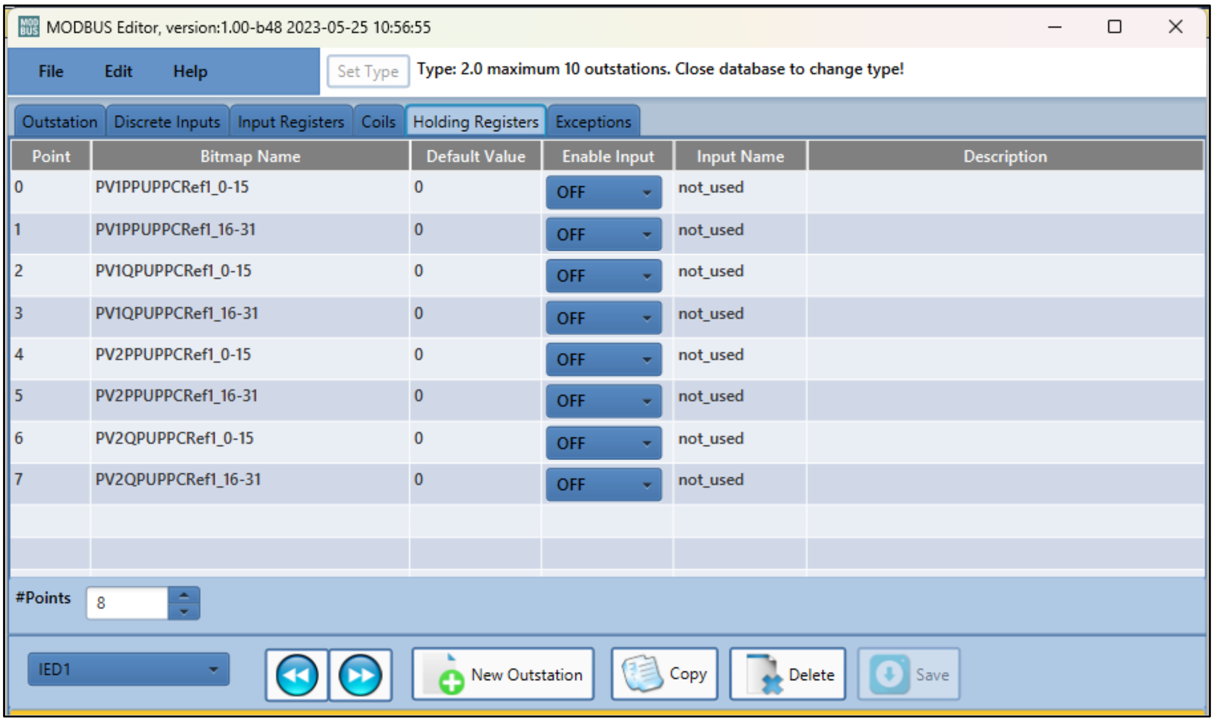

Figure 3.11: RSCAD FX Modbus Database File – Holding Registers

Using the above configuration of the Modbus Database File and consolidating it into a signal list, as seen in the definition of the Modbus Registers from Chapter 2.3.2, we edit the table to contain the mapped data for each register, as seen below in Table 3.2 Modbus Signal List.

Table 3.2: RSCAD FX GTNETx2 Modbus Signal List

Item	Modbus Signal List: Discrete Input		
	Description	***Register Address***	***Comment***
1	PV1DBlk1	BIT 0	0=open; 1=close
2	PV1DBlk2	BIT 1	0=open; 1=close
3	PV2DBlk1	BIT 2	0=open; 1=close
4	PV2DBlk2	BIT 3	0=open; 1=close
5	MainBrk	BIT4	0=open; 1=close
Item	**Modbus Signal List: Input Registers**		
	Description	***Register Address***	***Comment***
1	PVF1PGPUfilt_0-15	0	U16
2	PVF1PGPUfilt_16-31	1	U16
3	PVF1QGPUfilt_0-15	2	U16
4	PVF1QGPUfilt_16-31	3	U16
5	PVF1VGPULLrmsFilt_0-15	4	U16
6	PVF1VGPULLrmsFilt_16-31	5	U16
Item	**Modbus Signal List: Coils**		
	Description	***Register Address***	***Comment***
1	MainBrkPPC	BIT 0	0=open; 1=close
2	PV1DBlk1PPC	BIT 1	0=open; 1=close
3	PV1DBlk2PPC	BIT 2	0=open; 1=close
4	PV2DBlk1PPC	BIT 3	0=open; 1=close
5	PV2DBlk2PPC	BIT 4	0=open; 1=close
6	PV1DBlk1PPC	BIT 5	0=open; 1=close
Item	**Modbus Signal List: Input Registers**		
	Description	***Register Address***	***Comment***
1	PV1PPUPPCRef1_0-15	0	U16
2	PV1PPUPPCRef1_16-31	1	U16
3	PV1QPUPPCRef1_0-15	2	U16
4	PV1QPUPPCRef1_16-31	3	U16
5	PV1PPUPPCRef1_0-15	4	U16
6	PV1PPUPPCRef1_16-31	5	U16
7	PV1QPUPPCRef1_0-15	6	U16
8	PV1QPUPPCRef1_16-31	7	U16

3.2.5 SEL 3555 RTAC (PPC) Configuration:

The configuration is simplified since the example case composed by Christian Jeguers provides the SEL RTAC project file. It is using the SEL AcSELerator RTAC software to load the software onto the SEL 3555 RTAC. The successful loading of the example case onto the SEL 3555 RTAC is shown below in Figure 3.12. It is noticed that the under devices in the left windowpane show the GTNETx2_MODBUS server that is created on the SEL RTAC. As described in Chapter 2.2, the Modbus Server would be the simulation, and the SEL 3555 RTAC take on the role of the Client. Therefore, the IP address provided in the 'Settings' tab displayed below shows the IP address of the GTNETx2 card attached to the RTDS NovaCor.

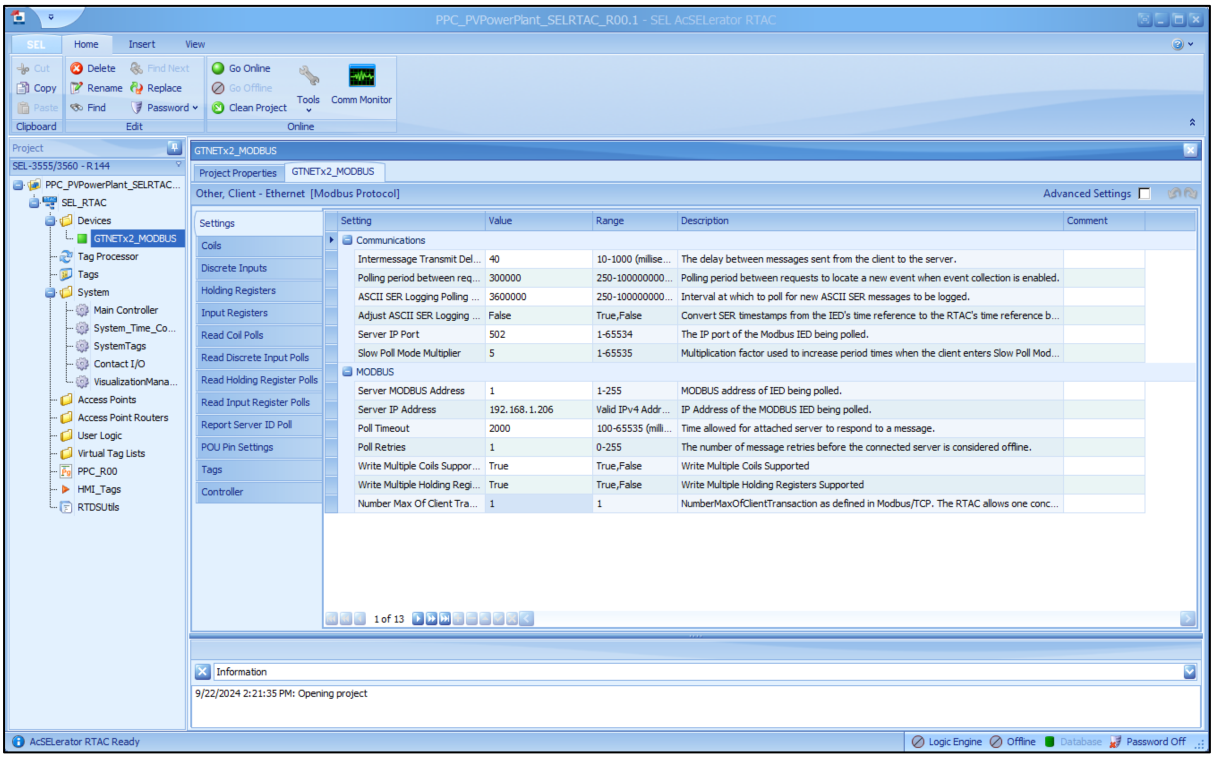

Figure 3.12: SEL 3555 RTAC Modbus Server Settings

Below the 'Settings' tab is a tab that lists each of the registers and provides a signal list for each signal. These are all compiled in the tab 'Tags' shown below in Figure 3.13. The SEL RTAC includes functionality to monitor these 'Tags' in real-time. Depending on the data type, controlling these tags is also possible with the SEL RTAC.

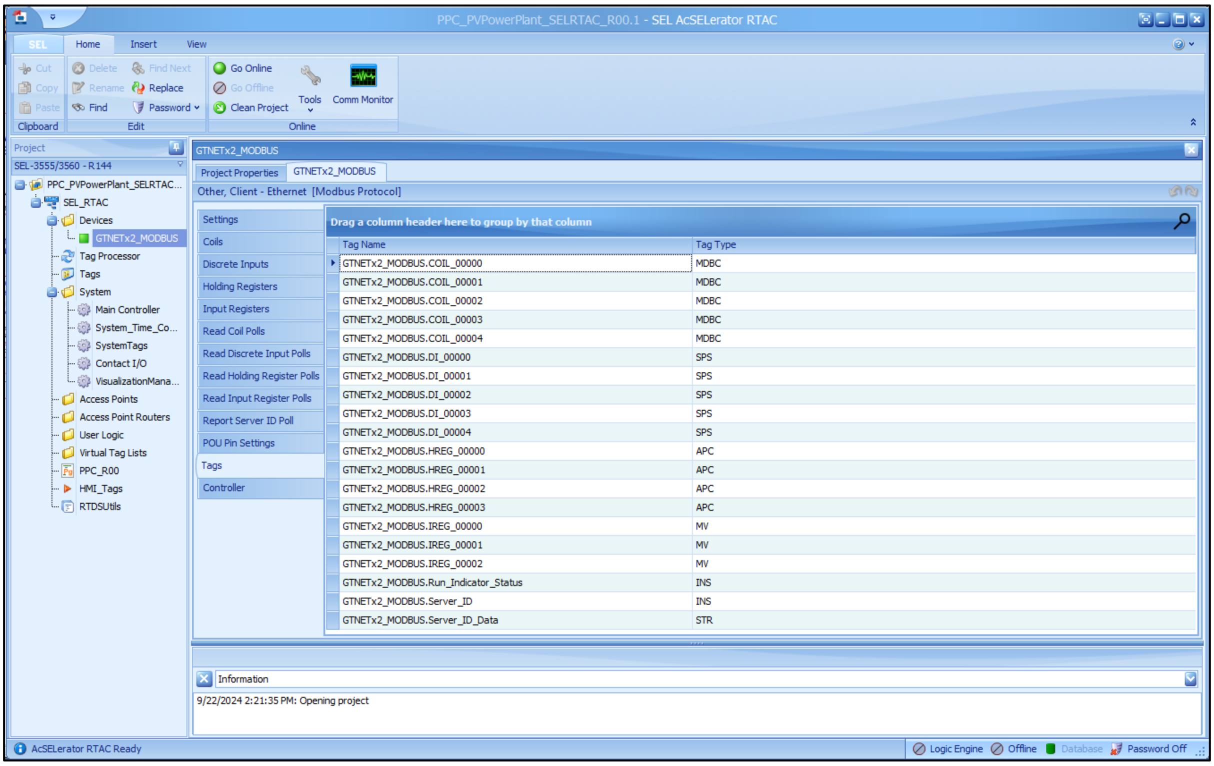

Figure 3.13: SEL 3555 RTAC Modbus Server Tags

3.2.6 RTDS Firmware Configuration and Initialising the Simulation - Modbus:

To capture data between the RTDS NovaCor and the SEL 3555 RTAC, a successful simulation is required on both devices. Now that the initial configuration is complete, it is essential to establish that they can simulate the PV system and interact with one another. This section looks at the RSCAD Fx Draft panel after a design has been compiled. Once the draft has been compiled, it can be loaded onto the RTDS NovaCor for real-time simulation. The simulation will be in the initial state with all breakers open and no readings in the measurement plots. The SEL AcSELerator RTAC software project file is then loaded onto the SEL 3555 RTAC and made to go ‘Online’. The successful configuration is verified by monitoring the ‘Controller;’ tab in the RTAC.

Firstly, the RSCAD Fx draft case is achieved before looking at the compiling. Ensuring the appropriate firmware is loaded on the GTNETx2 card is required. To achieve this, the ‘Firmware Upgrade Utility’ scans for the existing firmware. The existing firmware can then be modified to a list of firmware available. Concerning Figure 3.14 below, the latest firmware for Modbus protocol is selected and is seen by the denoted firmware ‘MODBUS 1.24’. In the ‘Firmware Utility’, the IP address is provided for the GTNETx2 card connected on Rack 5: Port 3. This is the same IP address configuring the Modbus Server in the SEL RTAC under Settings.

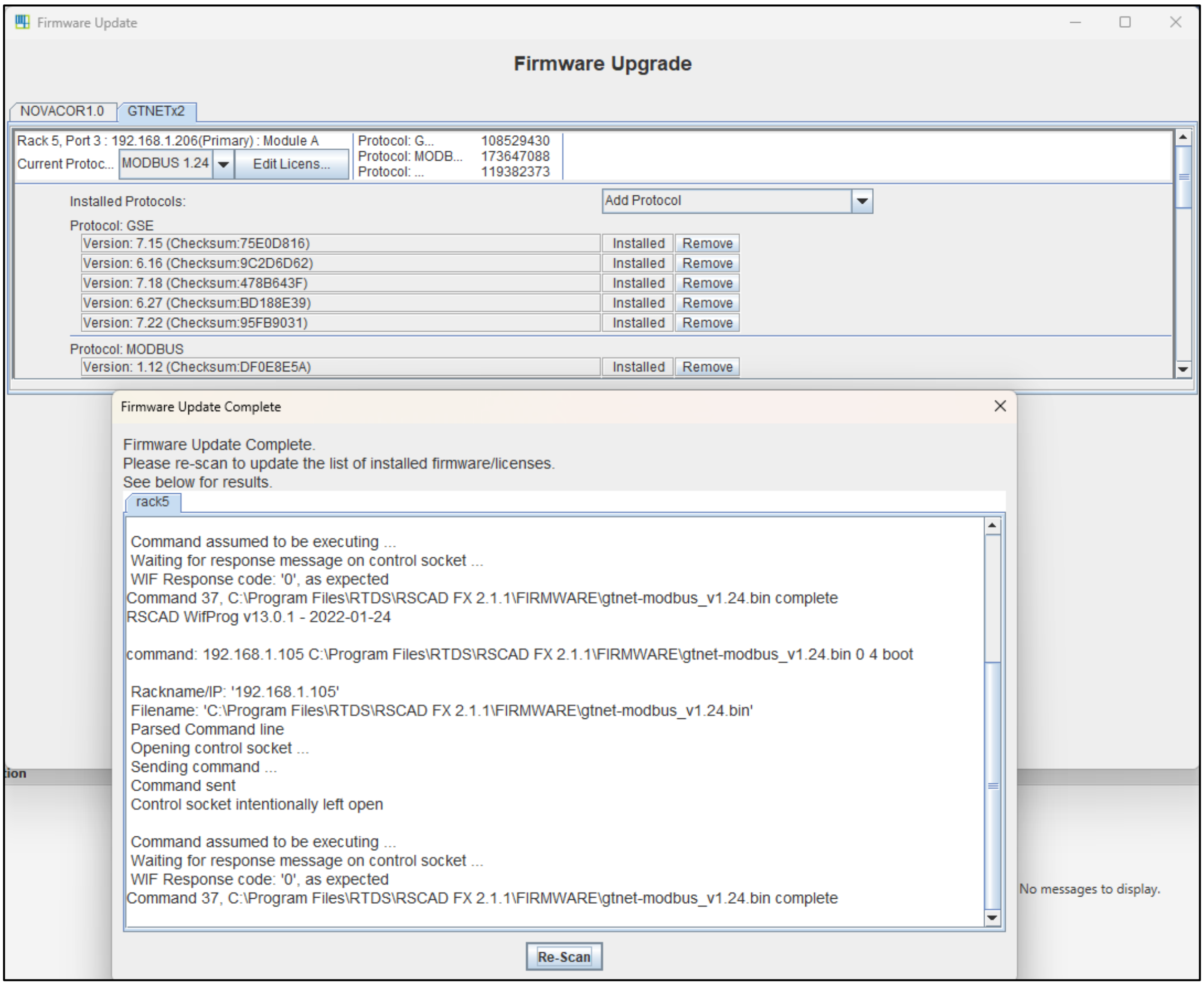

Figure 3.14: RSCAD Fx Modbus Firmware Utility Upgrade

After the appropriate protocol and latest firmware version are loaded onto the GTNETx2 card, ensuring this firmware has been successfully updated is good practice. A method to validate this is to use the ‘Config File Editor’. On the top right of the ‘Config File Editor’ is an icon that comments state it is used to get rack/switch configuration. Using this icon to initiate a scan, a list of available devices appears. The RTDS NovaCor (IP address 192.168.1.105) is connected to Rack 5, as noted below in Figure 3.15. Analyzing the input and output (IO) ports, we see an IO Card on ports 3 and 4. This IO card is loaded with GTNETx2_MODBUS firmware.

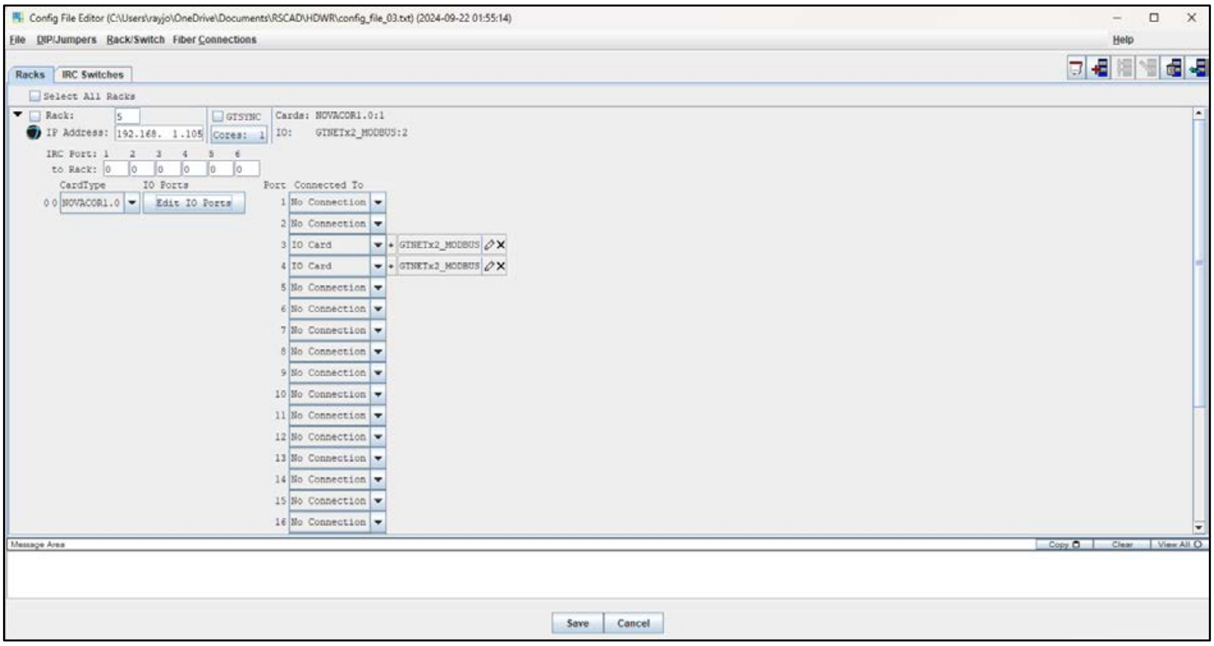

Figure 3.15: RSCAD Fx Modbus Config File Editor for NovaCor

The IO card is attached after the appropriate configuration is applied to the GTNETx2 card's firmware, and the port of the RTDS NovaCor is confirmed. The IP addresses have been confirmed and fit within the LAN established at the lab. The compilation of the RSCAD Fx draft case is completed using Rack 5. A verification message appears in the message pane at the bottom of the draft window, as seen in Figure 3.16 below.

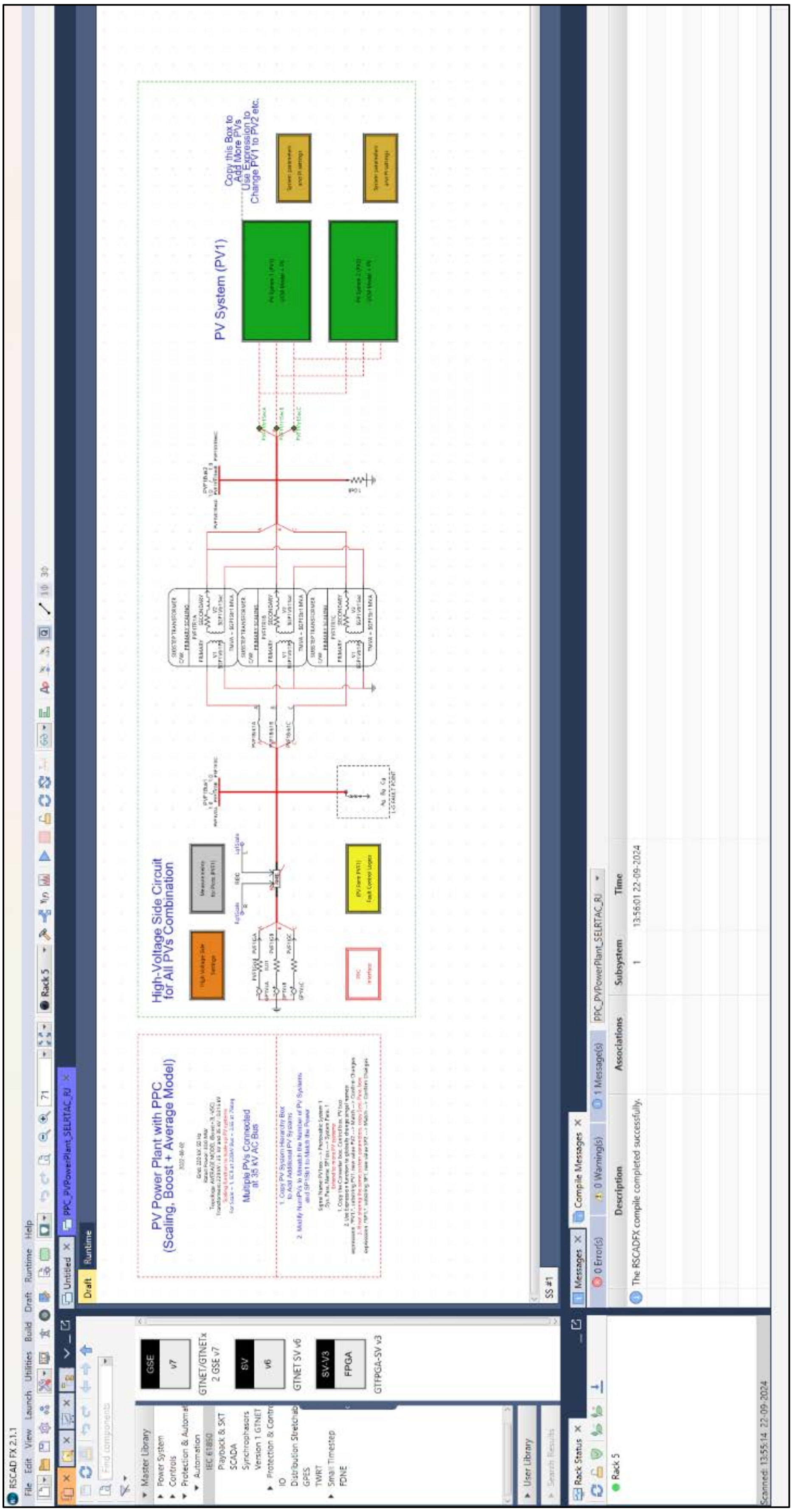

Figure 3.16: RSCAD Fx PPC_PVPower_Plant_SEL RTAC_R01 Compiled

With the draft case compiled, the simulation can be started using the ‘Run Case’ icon. Once the simulation is ‘live,’ the RTDS NovaCor processes the data in real time. Therefore, the initial state can be observed in the RSCAD Fx Runtime window. Since the initial state of the breakers is configured to be ‘open,’ no power flows from either of the PV systems into the HV transformer. Reference Appendix: A RSCAD Fx Runtime Initial State. Notice that the breaker indicator lights are ‘green’, stating that the breakers are in the ‘open’ state.

With the simulation running and real-time data being monitored on RSCAD Fx Runtime, the next step is get the PPC ‘online. To achieve this, the SEL AcSELerator RTAC software is used. The project file discussed in Chapter 3.2.5 is then selected to ‘Go Online’. This involves providing the SEL 3555 RTAC’s IP address, username, and password. Warning prompts list that the program loaded on the SEL 3555 RTAC should be changed to the project file currently being pushed, and any existing file should be removed. With the new project loaded on the SEL 3555 RTAC, the next step is ensuring successful communication. This can be done using the ‘POU’ tab in the SEL AcSELerator software, as seen below in Figure 3.17. The ‘POU’ diagram displayed below represents a card with registers that are either ‘TRUE’/’FALSE’ or display a value. Note that on the card's top corners, the registers ‘EN’ and ‘ENO’ for enabled are providing data as ‘TRUE’. This states that the software is ‘online’ and the SEL 3555 RTAC is actively executing the new program. On the left-hand column, the registers for Modbus registers Coils, Discrete Inputs, and Input Registers are set to ‘TRUE.’ On the right-hand side of the card, the register for ‘offline’ states ‘TRUE’, which only changes to ‘FALSE’. It has successfully established the communication between the GTNETx2 card via the TCP/IP protocol. As soon as that is established, the message sent and receive registers can be monitored to see if any failed packets are being transmitted.

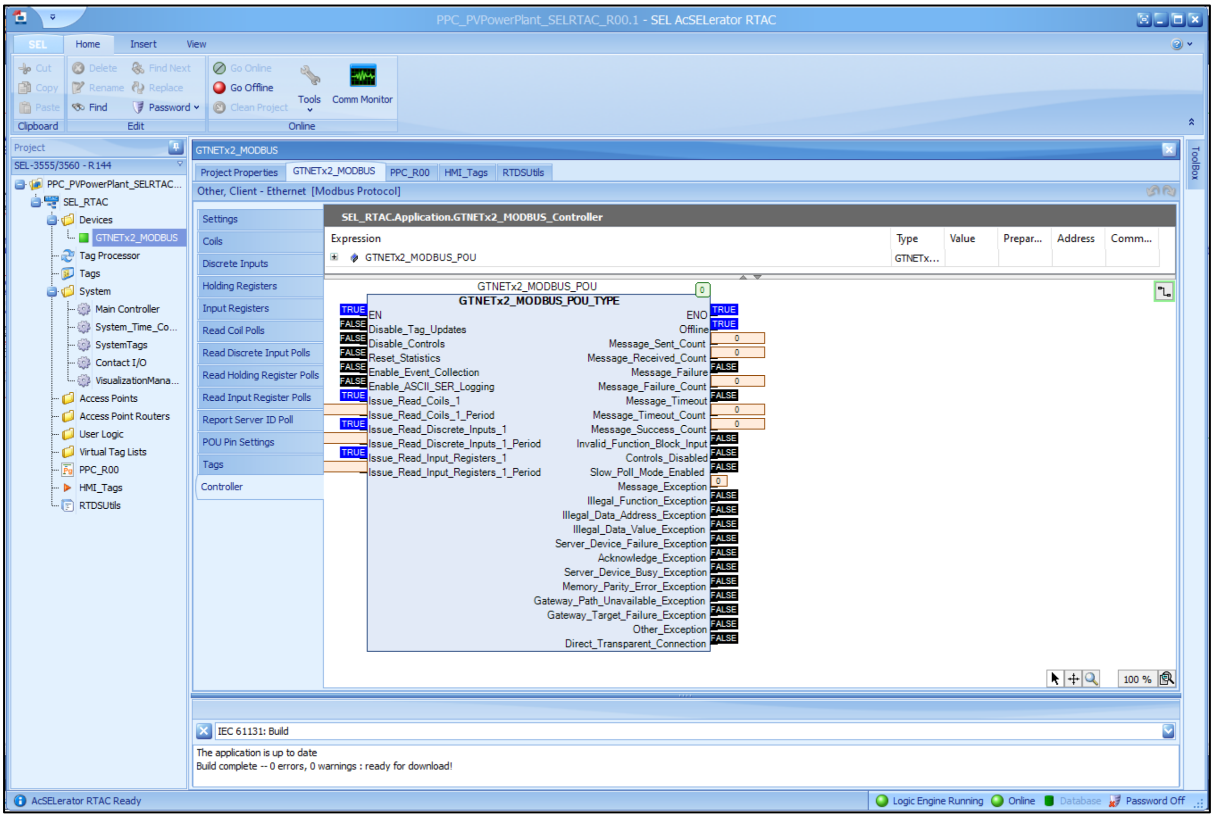

Figure 3.17: SEL AcSELerator RTAC ‘POU’ for Active Communications

3.3 IEC 61850 MMS Protocol Simulation

The IEC 61850 MM protocol simulation utilizes the same PV system simulation compiled for the previous PPC Power Plant setup discussed in Chapter 3. However, the RSCAD Fx communication module must be exchanged with a GTNETx2 GSE v7. This GTNETx2 GSE v7 is compatible with IEC 61850 standard protocols and requires the firmware of the RTDS NovaCor to be adjusted to a matching version. Therefore, the SEL 3555 RTAC configuration needs to be reconfigured to be compatible with the new communication module of the RTDS. As noted in Chapter 2.4, Figure 2.23 shows the equipment configuration in the lab scale implementation. The GPS clock was unavailable at the current simulation time, but it must be noted that with this configuration, accurate timestamping would have been provided in the data.

3.3.1 Lab-Scale Setup for IEC 61850 Simulation:

The IEC 61850 MMS protocol simulation requires the GTNETx2 card of the NovaCor to be loaded to the updated GTNETx2 GSE v7.24 (latest) firmware. The appropriate LAN configuration must follow the LAN configuration discussed in Chapter 2.4 Figure 2.15. The IP addresses of the devices connected in the network are consistent with those seen in Table 3.3: Modbus Protocol Simulation – IP Addresses. This ensures that using an IP to reference is consistent across both simulations. The IP addresses for the IEC 61850 protocol simulation can be seen below in Table 4: IEC 61850 MMS Protocol Simulation – IP Addresses, with the last two line items being highlighted grey as they not being available in the lab during this simulation.

Table 3.3: IEC 61850 MMS Protocol Simulation – IP Addresses

Item	Device Description	IP Address
1	RTDS NovaCor	192.168.1.105
2	GTNETx2 GSE V7.24	192.168.1.205
3	SEL 3555 RTAC (PPC)	192.168.1.170
4	Operator PC	192.168.1.199
5	Ethernet Switch	192.168.1.15
6	GPS Clock	Not available
7	GTSYNC Card	Not available

3.3.2 IEC 61850 MMS RSCAD FX Draft PPC Interface Hierarchy:

A new project file is created by saving the existing RSCAD Fx PPC_PVPowerPlant_SELRTAC under a new file name and folder. All files that are attached to the simulation, such as the configured IED description (CID) file for the GTNETx2 GSE v7 configuration. The PV system's working components are consistent with the new RSCAD Fx project file. The only modifications occur to the communication parameters of the simulation. Therefore, the hierarchy 'PPC Interface' box should be modified in the draft case. Firstly, note that the GTNETx2 component used to interact with the GTNETx2 card attached to the RTDS NovaCor (192.168.1.206) is a new component from the RSCAD Fx library. The component selected for this simulation is the latest GTNETx2 GSE version 7 version. This software component requires the firmware of the actual GTNETx2 card to be updated, as seen in the following subsection. It must be understood that the mapping of signal lists is approached very differently between the Modbus and the IEC 61850 MMS protocol. Therefore, a new layout appropriate to the IEC 61850 standard is used for the draft case of the signal names. Instead of Modbus registers, the modified PPC Interface maps the signal data into datasets. This is consistent with the configuration of the GTNETx2 GSE v7 using the IED Configuration Tool (ICT) software plugin designed for configuring IEC 61850 standard protocols and discussed in the following sections. The signal mapping for the IEC 61850 MMS communication is seen in Figure 3.18 below.

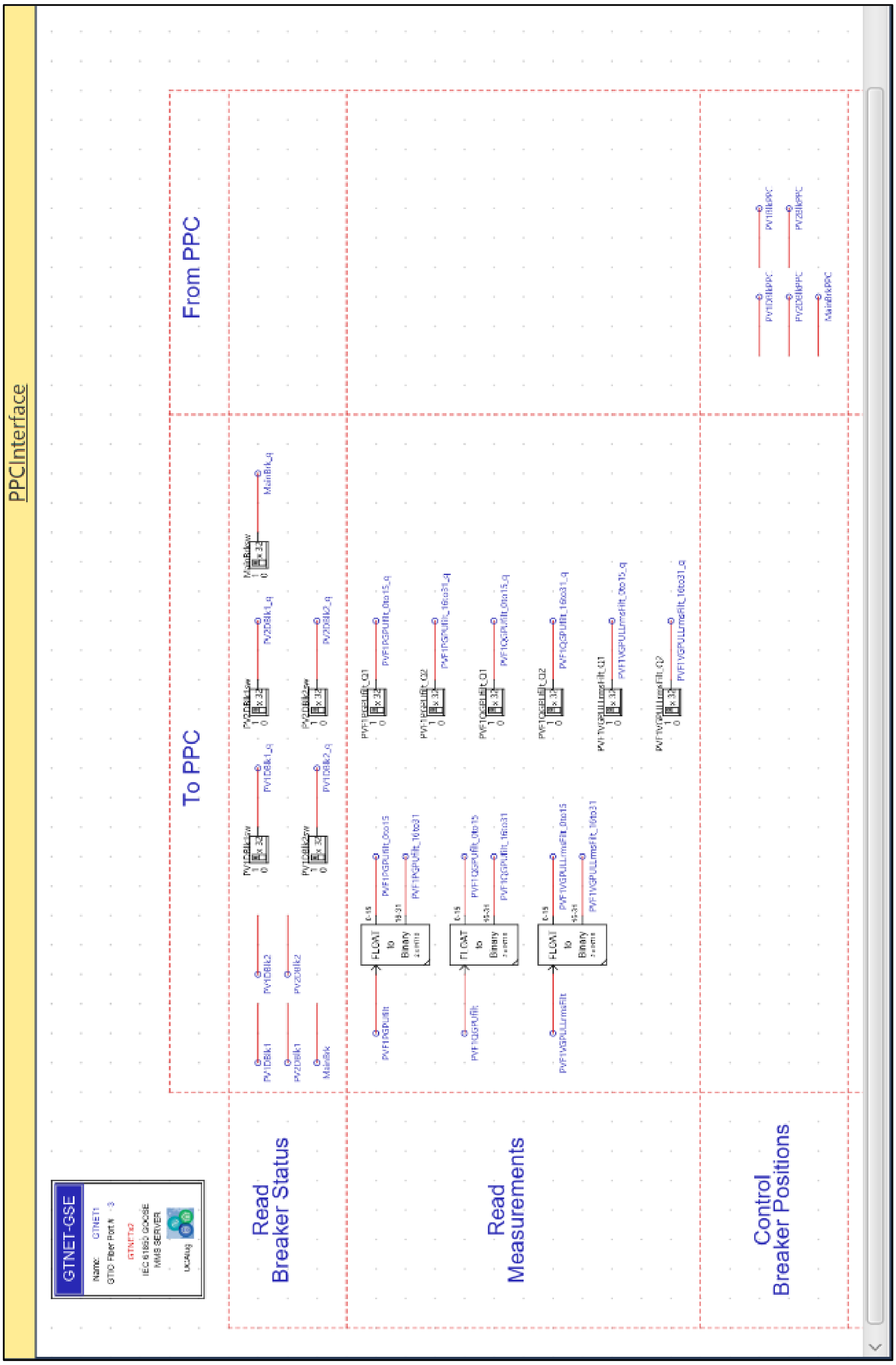

Figure 3.18: RSCAD Fx PPC Interface – MMS Configuration

3.3.3 GTNETx2 GSE V7 Configuration

The GTNETx2 GSE V7 component is the RSCAD Fx draft element for configuring the IEC 61850 standard protocols. Its configuration must contain fibre ports that the GTNETx2 communication module is linked to the RTDS NovaCor as seen in Figure 3.19 below.

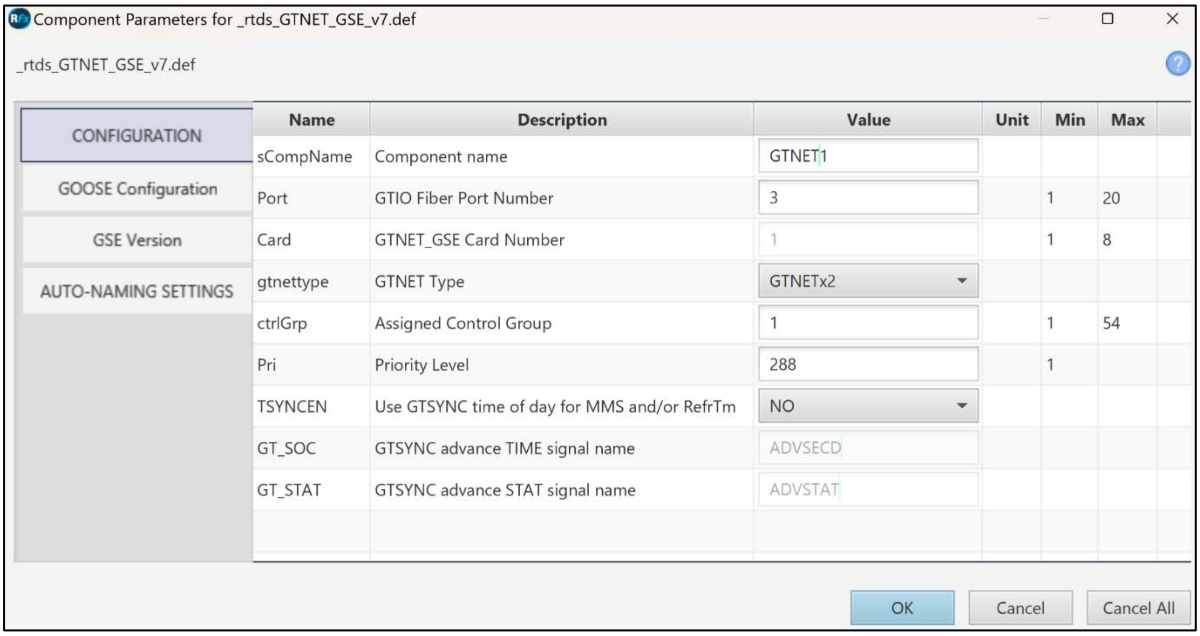

Figure 3.19: RSCAD GTNETx2 GSE V7 – MMS Configuration

3.3.4 ICT Configuration

The ICT (IED Configurator Tool) software provides the platform to configure the GTNETx2 card to communicate using IEC 61850 standard protocols. The mapping of signals for the IEC 61850 standard protocols is achieved by assigning signal names to Logical Nodes (LN). These LNs are categorised into datasets (DS). Specifically focusing on the IEC 61850 MMS protocol, these DS are used for reports and polls. Before any of this mapping, the general settings of the GTNETx2 card must be defined in the ‘Access Point’. Tab, as seen below in Figure 3.20. The IP address specified in the ICT must match the IP address of the GTNETx2 card attached to the RTDS NovaCor. The size of the LAN defines the subnet mask, and the gateway may be left out as all the devices connected to the lab experiment fall within the same subnet mask. The TCP is assigned to port 102.

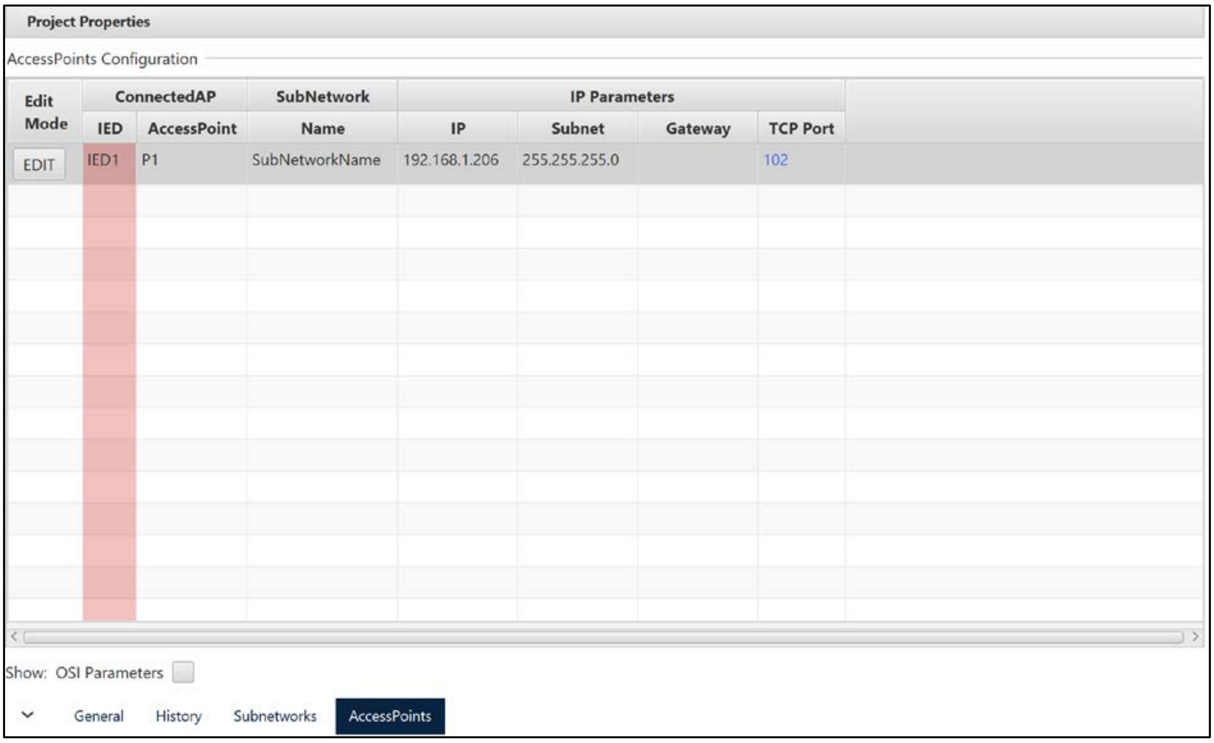

Figure 3.20: RSCAD Fx ICT – Access Point Configuration

After the network parameters are configured the signal mapping is achieved by assigning LN in the 'IED Model tab. The 'IED Model' tab lists all LNs available for a GTNETx2 GSE V7 that match that of the LNs expressed in the second edition of the IEC 61850 standard. Furthermore, option schema is provided for RTDS integrated control. This is only relevant for achieving control of switchgear in the RSCAD Fx simulation environment, and since this report focuses on monitoring, this schema is not applied to any LNs. The 'IED1' is the name provided to the virtual IED to communicate with the RSCAD FX simulation. This 'IED1' falls underneath the GTNET1 component, which was the name of the GTNETx2 GSE V7 found in the 'PPC Interface' hierarchy box. Two LNs are selected in the 'IED Model' tab, 'XCBR' for circuit breakers and 'GGIO' for generic input/output used for measurements. For each breaker signal, names found in the 'PPC Interface' hierarchy box are assigned to individual 'XCBR' LNs, whereas the read measurement signals can be categorized under a single 'GGIO' LN. These LNs are pulled under IED called NewDevice and are placed with system LNs 'LLNO' LN zero and 'Obj0LPHD0' related to physical device information such as nameplate and operation counters. The table of associated LN can be referenced from IEC 61850-7-4-2 'Basic communication structure – Compatible logical node classes and data classes' standard. Figure 3.21 below is the LN associated with the virtual IED labelled 'IED1'.

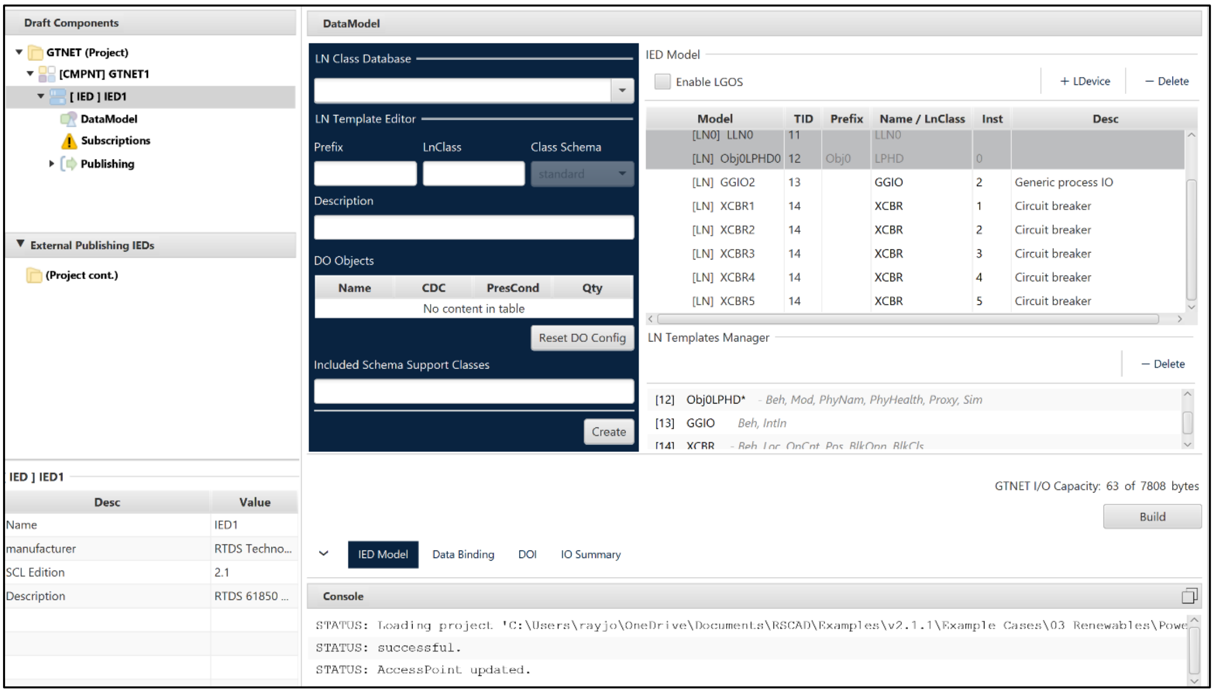

Figure 3.21: RSCAD Fx ICT – IED Model

After defining the LNs required in the ‘IED Model’ tab, the next step in the configuration is achieved on the ‘Data Binding’ tab. This is a crucial step in configuring the signal names in the ‘PPC Interface’ hierarchy box to their respective Data Attributes (DAs). These Das fall under Data Objects (DOs) as discussed in Chapter 2.4, and once the DA of the LN has been configured, the text of the LN is displayed in ‘green’, noting that the configuration has been assigned. This process maps the signal names to Das of the LNs assigned to ‘IED1’. It is important to see the correlation between the RSCAD Fx signals and the mapping to respective Das. To show this correlation, the following figures provide exploded views for each LN assigned to ‘IED1. Figure 3.22 below shows the overview of the LNs assigned to ‘IED1’ and is achieved in the previous step defined by the “IED Model’ tab. All LNs are displayed in ‘green’ text because they have been configured with Das.

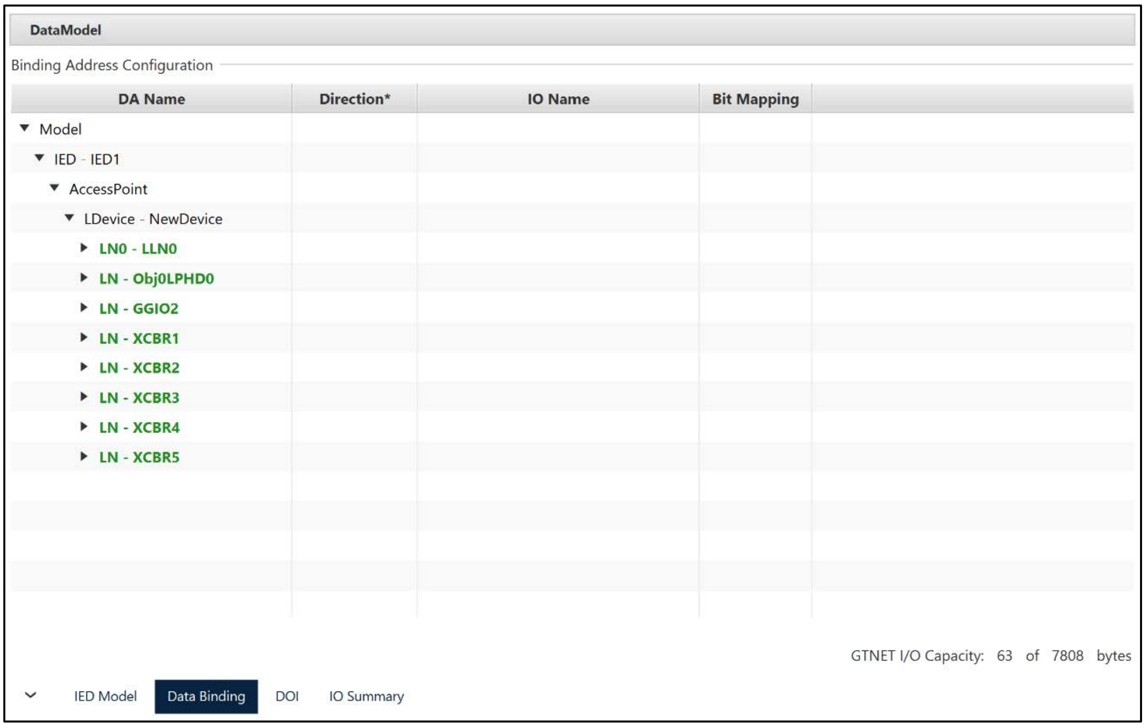

Figure 3.22: RSCAD Fx ICT – Data Binding Overview

Exploding the 'LLNO' the DO 'Mod' has had the DA 'stVal', 'q' and 't' configured so that the direction states is 'mms'. This states that the mode or behavior of the system LN, referred to as 'zero,' establish the status value, quality, and timestamp using the IEC 61850 MMS protocol. No 'IO Name' is associated with these DAs as these are not mapped to specific signals from the RSCAD Fx draft simulation, as seen in Figure 3.23 below. The same execution is configured for the 'LN – obj0LPHD0' Data Object (DO) 'Mod'. The reference to each DA is found using the IEC 61850-7-4 'Basic Communication Structure – Compatible Logical Node Classes and Data Object Classes.'

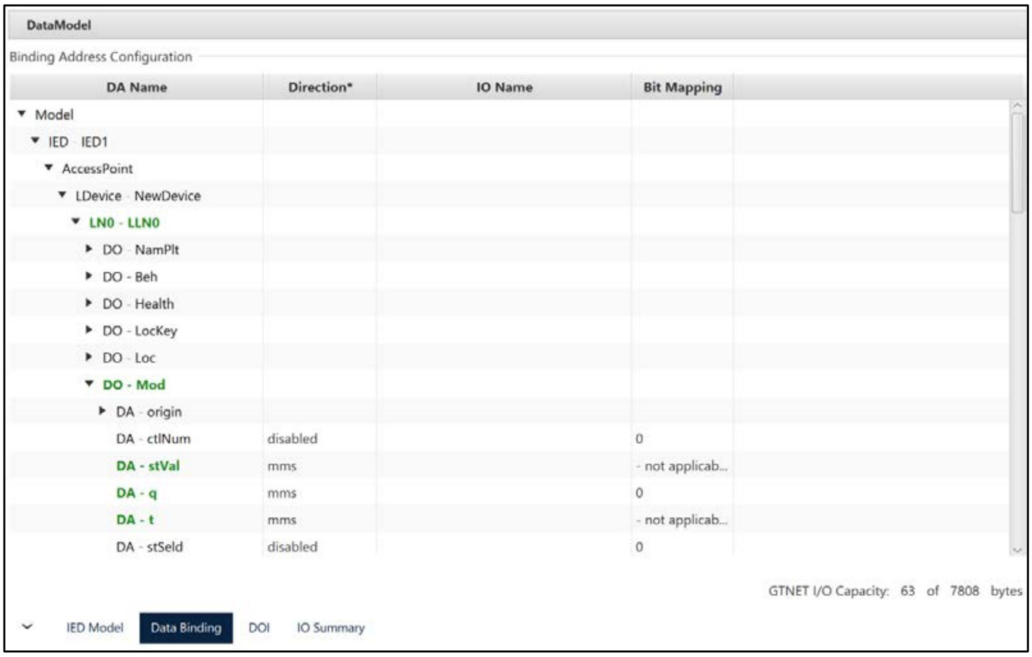

Figure 3.23: RSCAD Fx ICT – Data Binding LLNO

Continuing the Data Binding of the LNs developed in the ‘IED Model’ tab, the ‘LN – GGIO2’ is expanding for configuration of ‘DO – IntIn001’ (Integer Status Input according to IEC 61850-7-4). The ‘stVal’ (status value) is mapped as an output and associated with the signal name ‘PVF1PGPUfilt_0to15’ the first 16-bit integer from the Power Generation per unit ‘Float to Integer’ function block seen in the PPC Interface hierarchy of the RSCAD Fx. An additional signal name not present during the Modbus mapping is added called ‘PVF1PGPUfilt_0to15_q’ and is designed to provide data for the quality of the specific signal. The second integer from the ‘Float to Binary’ function block named ‘PVF1PGPUfilt_16to31’ and its associated quality bit, ‘PVF1PGPUfilt_16to31_q’ is assigned to ‘DO-IntIn002’ of the same ‘LN – GGIO2’ as noted below in Figure 3.24. In addition to the mapping of the signal name to the Das, the direction is also defined as an output. This means that the IED1 ‘NewDevice’ configured in the ICT platform takes the information from the simulation and encodes that into an outgoing message for an external device to read.

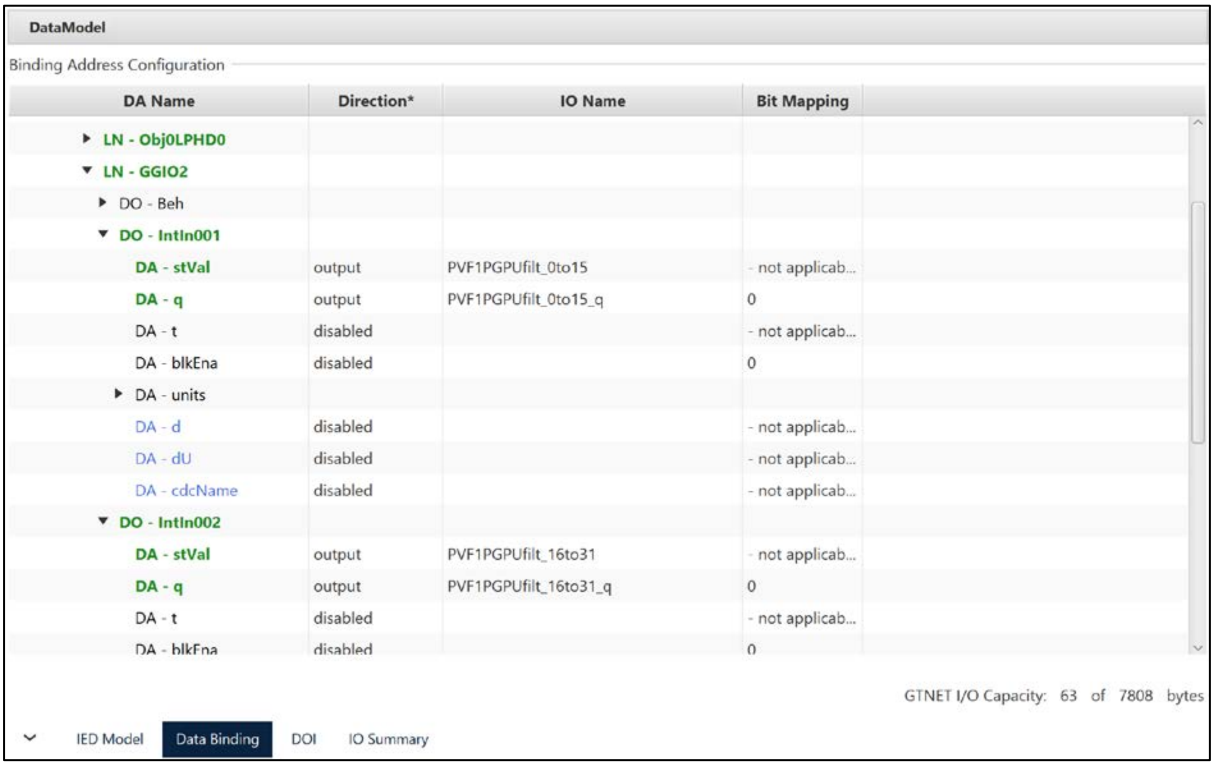

Figure 3.24: RSCAD Fx ICT – Data Binding GGIO (part 1)

The ‘LN – GGIO2’ is further explained by expanding the following DOs, ‘DO – IntIn003’ and ‘DO – IntIn004’. As seen before, the mapping to the signal names has been provided the DA ‘stVal’ and ‘q’ attributes of respective DOs. The direction is also established as data going from the simulation to the external device. These two DOs are associated with ‘PVF1QGPUfilt-0to15’ and ‘PVF1QGPUfilt-16to31’ as well as their quality bits noted as ‘PVF1QGPUfilt-0to15_q’ and ‘PVF1QGPUfilt-16to31_q’. These signals are the reactive power measurements per unit and output the ‘Float to Binary’ function block from the PPC Interface hierarchy of the RSCAD FX draft. This mapping is displayed in Figure 3.25 below.

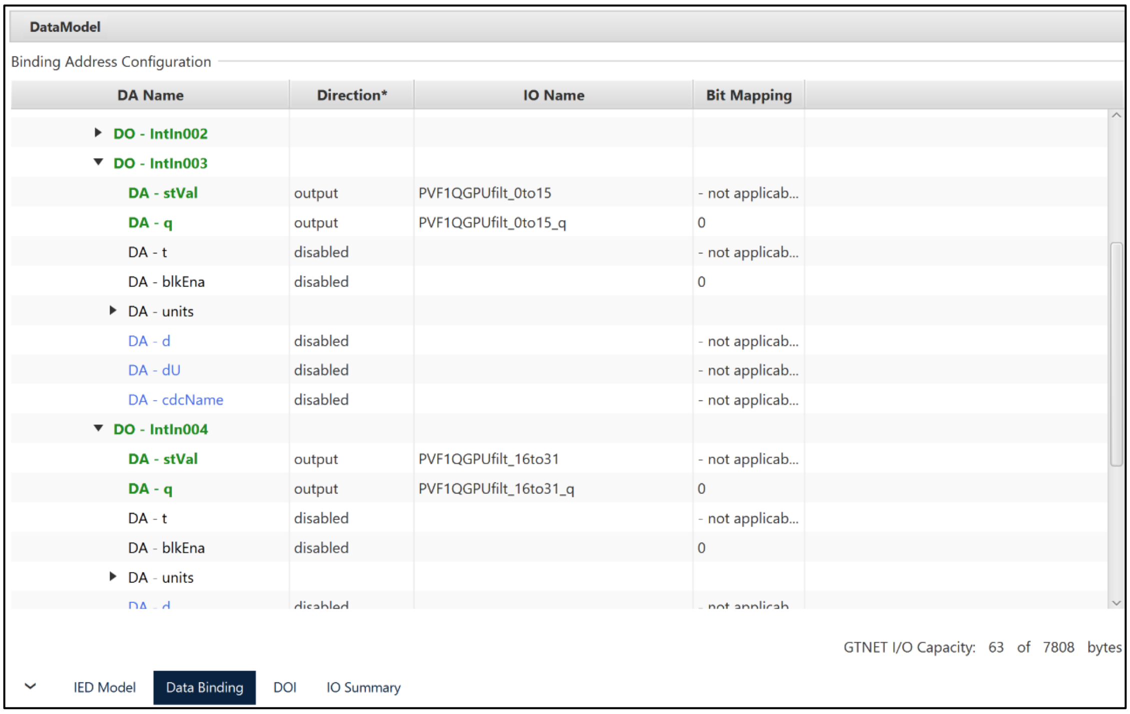

Figure 3.25: RSCAD Fx ICT – Data Binding GGIO (part 2)

The final two DOs encapsulated in the 'LN – GGIO2' are 'Do – IntIn005' and 'DO – IntIn006'. These conclude the measurement readings from the PPC interface and are mapped to appropriate DAs 'stVal' for 'PVf1VGPULLrmsFilt_0to15' 16 bit and 'PVf1VGPULLrmsFilt_16to31' for the second 16 bit of the 'Float to Binary' converter displayed in the PPC interface. Their respective quality bits are mapped, and their direction is set to output. These signals can be seen as mapped in the RSCAD Fx ICT tool in Figure 3.26

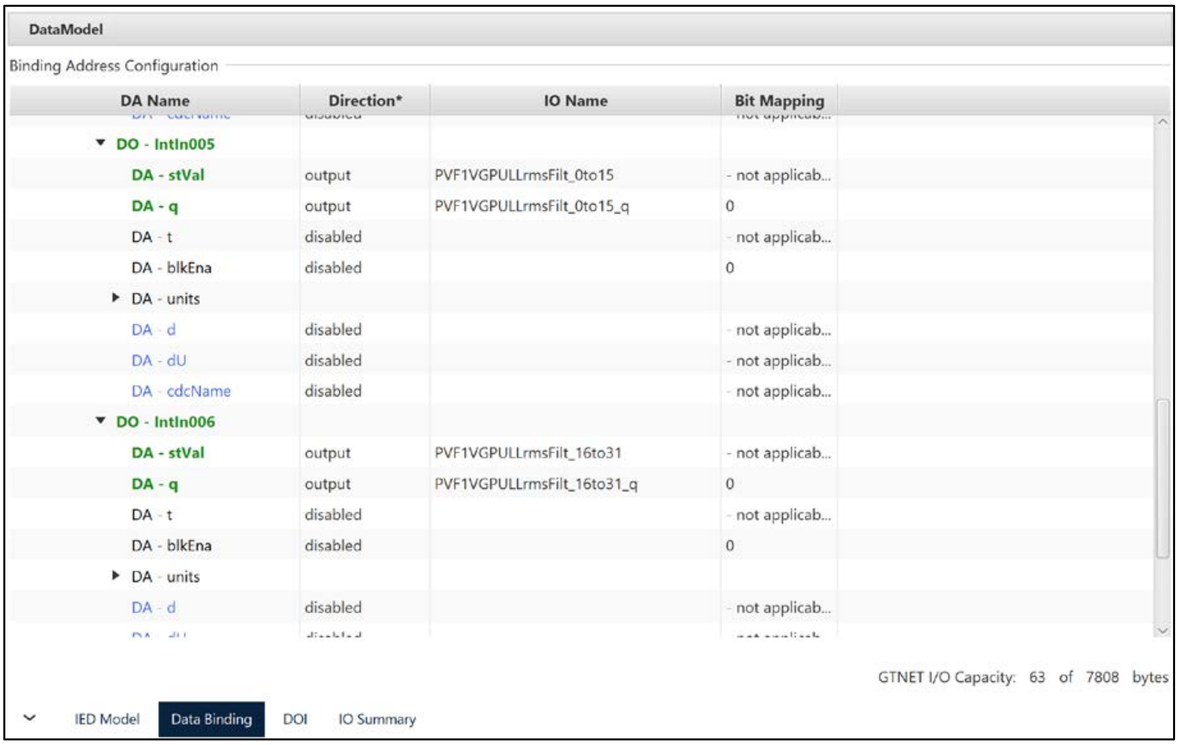

Figure 3.26: RSCAD Fx ICT – Data Binding GGIO (part 3)

After completing the data binding for the signals required for measurement, the following steps display the signal mapping for the breaker statuses. The breaker statuses are mapped to LN ‘XCBR1’ to ‘XCBR5’. Below in Figure 3.27 shows the ‘LN – XCBR1’ being mapped to the signal ‘PV1DBlk1’ using the ‘DA – stVal’ of the ‘DO – Pos’. This states that the circuit breaker logical node has been selected to map the position of the ‘PV1DBlk1’ breaker from the RSCAD Fx simulation. This is mapped to the circuit breaker data object called position using the data attribute ‘status value’. This provides a reading on the position of the breaker. The quality bit for the respective signal is then mapped to the same DO of the LN. This is repeated for all breaker positions listed in the PPC interface hierarchy.

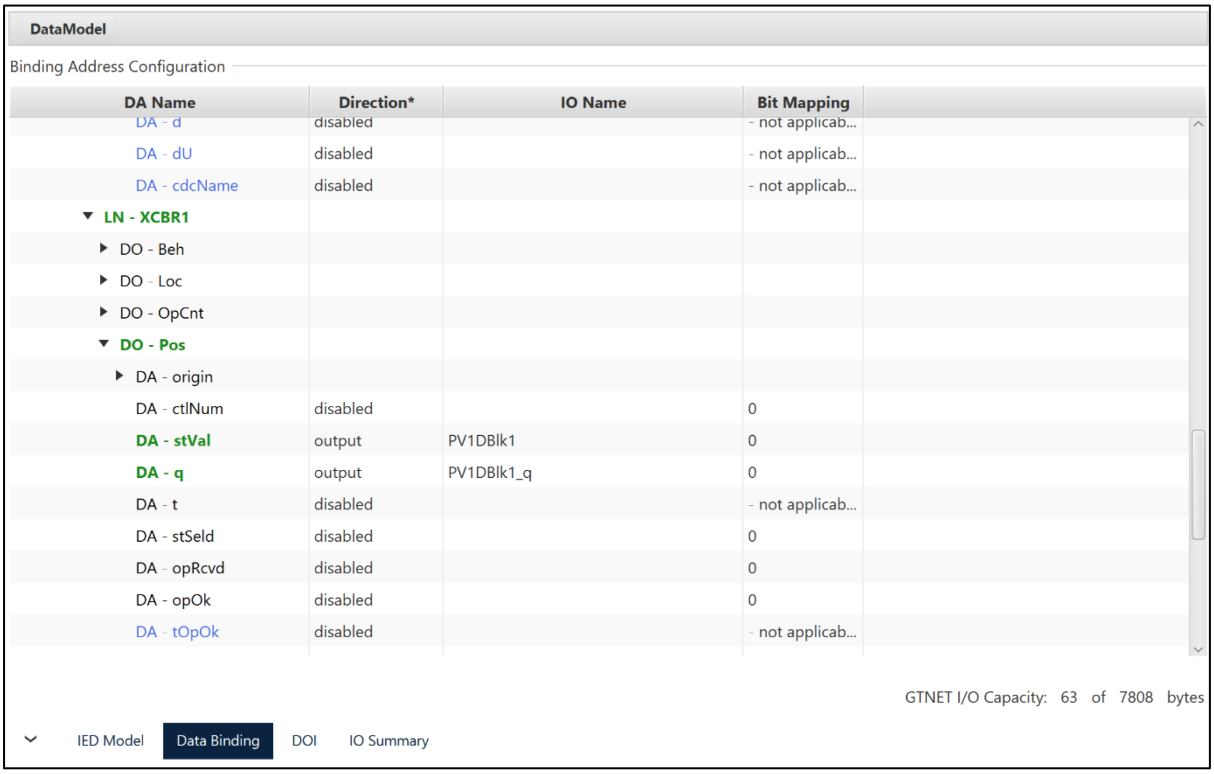

Figure 3.27: RSCAD Fx ICT – Data Binding XCBR1

In Figure 3.28, the ‘LN—XCBR2’ can be seen mapped to the signal ‘PV1DBlk2’. Once again, the signal has a quality bit, and both directions are configured as outputs.

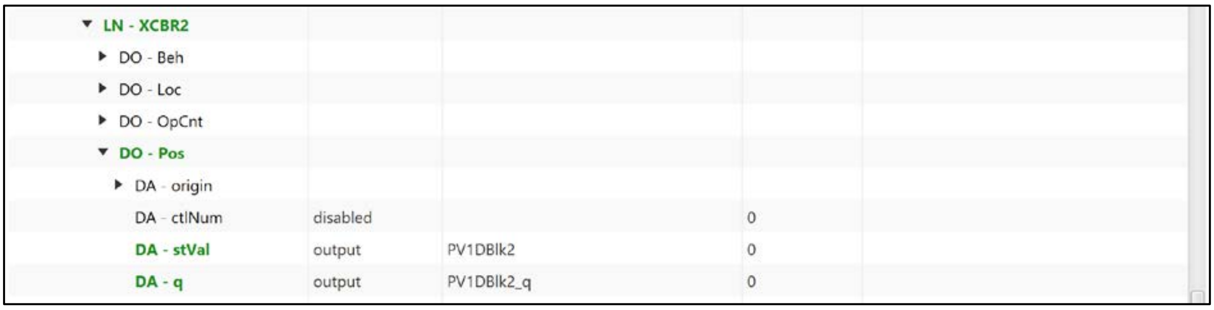

Figure 3.28: RSCAD Fx ICT – Data Binding XCBR2

In Figure 3.29, the ‘LN—XCBR3’ can be seen mapped to the signal ‘PV2DBlk1’. This is the first circuit breaker in the second PV System.

LN - XCBR3			
DO - Beh			
DO - Loc			
DO - OpCnt			
DO - Pos			
DA - origin			
DA - ctlNum	disabled		0
DA - stVal	output	PV2DBlk1	0
DA - q	output	PV2DBlk1_q	0
DA - t	disabled		- not applicab...

Figure 3.29: RSCAD Fx ICT – Data Binding XCBR3

In Figure 3.30, the ‘LN—XCBR4’ is mapped to the signal ‘PV2DBlk2’. This is the second circuit breaker in PV system 2.

LN - XCBR4			
DO - Beh			
DO - Loc			
DO - OpCnt			
DO - Pos			
DA - origin			
DA - ctlNum	disabled		0
DA - stVal	output	PV2DBlk2	0
DA - q	output	PV2DBlk2_q	0
DA - t	disabled		- not applicab...

Figure 3.30: RSCAD Fx ICT – Data Binding XCBR4

The final ‘LN—XCBR5’ is mapped to the primary breaker signal ‘MainBrk’. This is the breaker that closes both PV systems onto the HV transformer. It must be closed for any generation to provide data in the output signal in the measurement LN GGIO. This configuration is displayed in Figure 3.31 below.

LN - XCBR5			
DO - Beh			
DO - Loc			
DO - OpCnt			
DO - Pos			
DA - origin			
DA - ctlNum	disabled		0
DA - stVal	output	MainBrk	0
DA - q	output	MainBrk_q	0
DA - t	disabled		- not applicab...

Figure 3.31: RSCAD Fx ICT – Data Binding XCBR5

The following tab of the ICT platform provides a list of the data types for these signals. Navigating to the ‘DOI’ tab displays the list of LNs and their respective DAs, each associated with its data type. Concerning Figure 3.32 below, the data types for the measurement DO are found in the ‘LN—GGIO2’ are all defined as INT32 (32-bit integers).

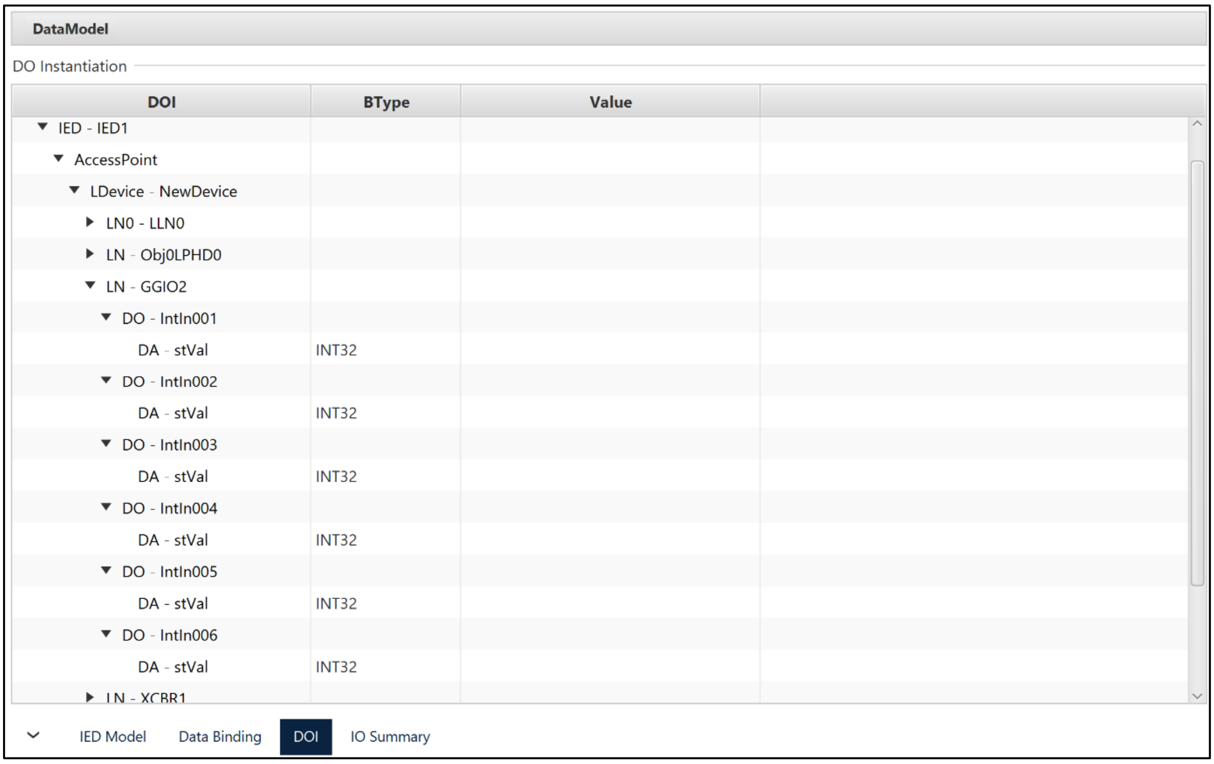

Figure 3.32: RSCAD Fx ICT – DOI GGIO2

The data types associated with the circuit breaker signals are different from those defined for the GGIO LN. Circuit breaker logic in the IEC 61850 standard uses the application of a double-bit status (DPS). This combination of two bits can be either in a state ‘0’ or ‘1’ providing a list of four possibilities. This provides more information than a traditional single-bit (BOOLEAN) logic. This is because the state of the DPS (or noted as ‘Dbpos’ in the ICT platform) is that the initial state ‘00’ generally refers to an error. The DA for the ‘stVal’ of the ‘DO – Loc’ is mapped as BOOLEAN as this is to send a signal to either open or close the breaker. Since this research does not cover control, its implementation is not highlighted. The Circuit Breaker signal mapping is displayed in Figure 3.33 below.

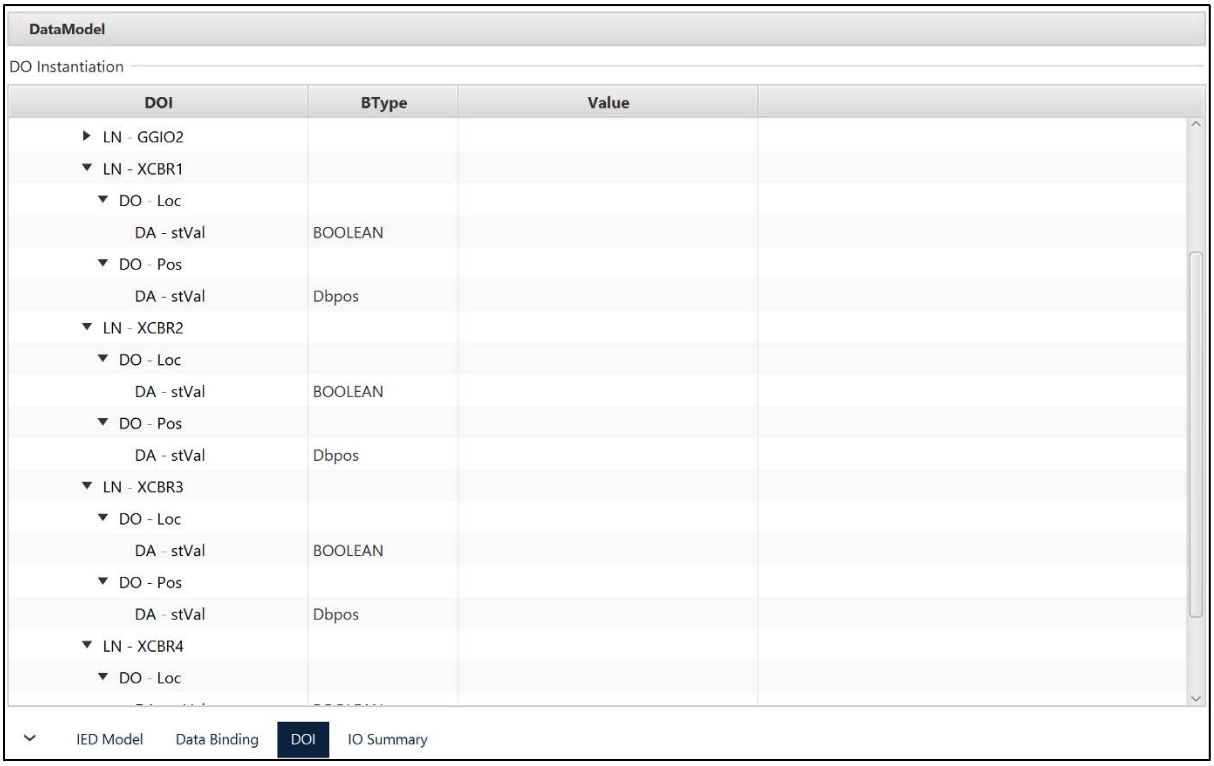

Figure 3.33: RSCAD Fx ICT – DOI XCBR's

After completing the data binding in the ICT software's 'IED Model' tab, the next step focuses on creating Datasets. This is important as IEC MMS works on the process by polling or reporting based on information contained within datasets. Measurement data and circuit breaker statuses categorize the two datasets. Below in Figure 3.34, the dataset 'BreakerStatus' is created to house the LNs 'XCBR1' to 'XCBR5' associated with the breaker positions. Similarly, the dataset 'Measurements' houses the LN GGIO and is based on obtaining readings of the output of the PV systems. The information regarding the 'Measurement' datasets can be seen in Figure 3.35.

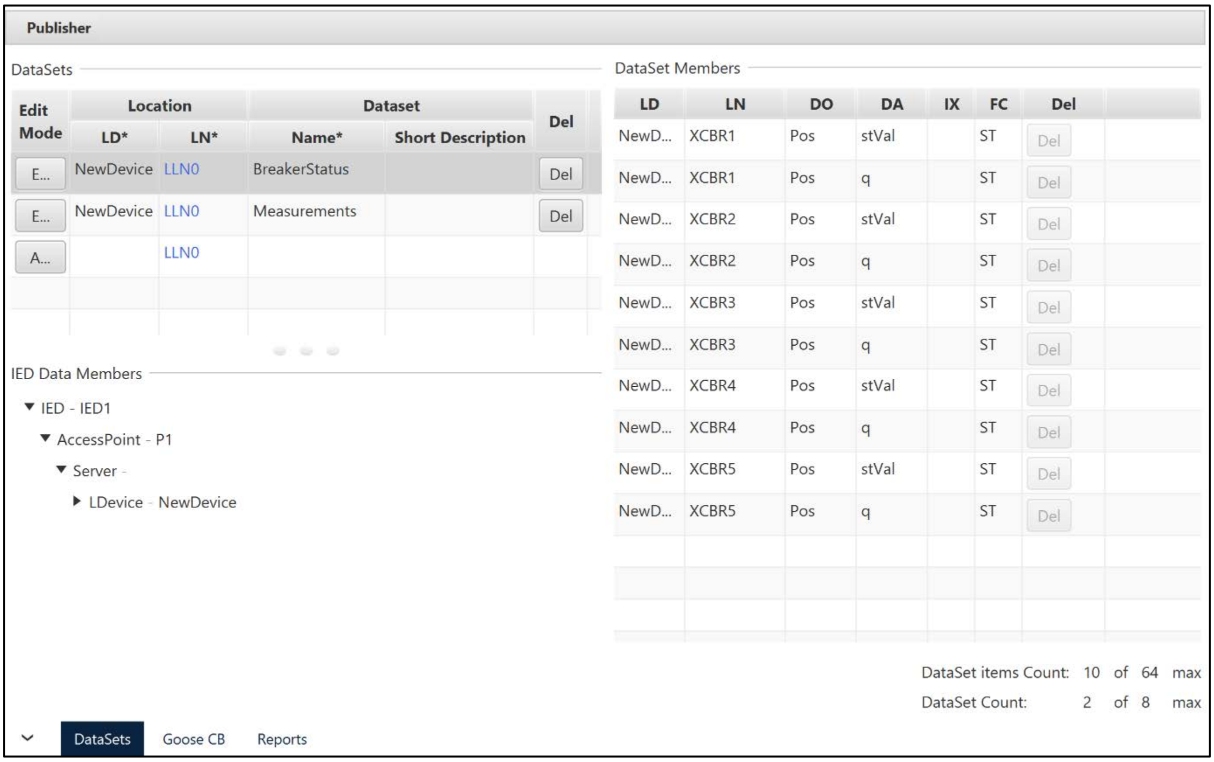

Figure 3.34: RSCAD Fx ICT – Dataset ‘BreakerStatus’

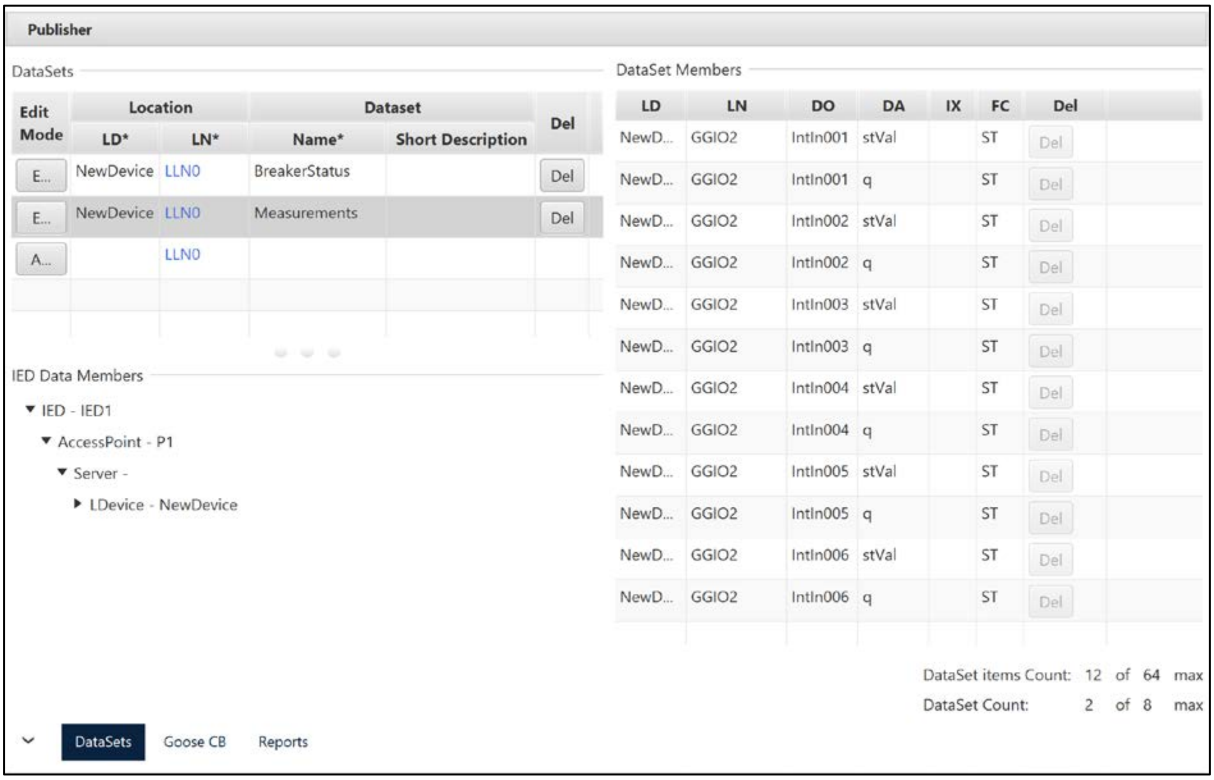

Figure 3.35: RSCAD Fx ICT – Dataset ‘Measurements’

These datasets are then assigned to reports. The name of the reports reflects the contents of the datasets. Report ‘BrkPos’ is linked to the ‘BreakerStatus’, and the report ‘MeasuredVal’ is related to the dataset ‘Measurements’. These reports are configured to be buffered by 1000 and 2000 milliseconds, respectively. A buffered report provides additional functionality that is not available for Modbus. The buffered report ensures reliable communication of critical data in situations where interruptions or delays occur. The data is stored in a “buffer” of the server’s memory if the communication with the client is temporarily unavailable. Once the connection is re-established, the data will be transmitted. Another mode of implementing reports is based on ‘Event-Driven Reporting.’ This means that when a change of state of predetermined data occurs, an event-driven report is initiated to communicate instantly. Unlike Modbus, which can only poll data at predetermined intervals, the ‘event-driven reports’ provide much faster communication of critical system changes. The configurations of these reports is displayed below in Figure 3.36

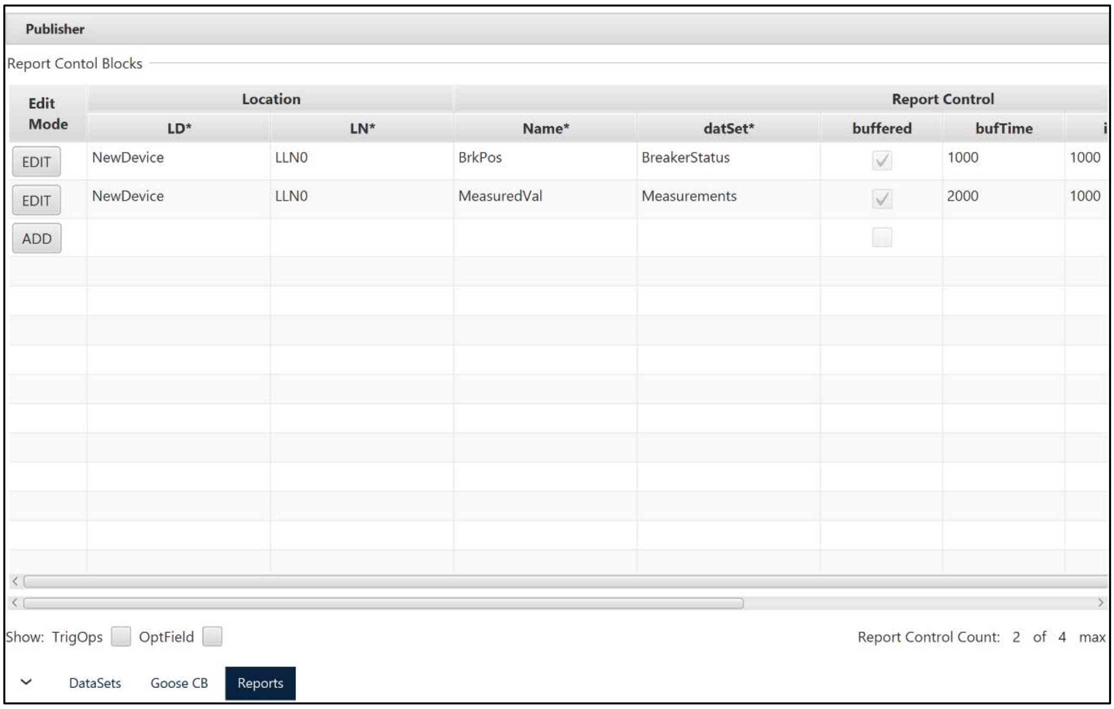

Figure 3.36: RSCAD Fx ICT – Reports

The shared data classes from the IEC 61850-7-4 standard show the data associated with the Logical Nodes used in the simulation. The two LN used in this simulation are GGIO and XCBR. These LN are associated with respective data objects and data attributes. Each data attribute has an associated data type. These are seen below in Figure 3.37 and Figure 3.38 as extracts from the standard.

GGIO class				
Data Name	**Common Data Class**	**Explanation**	**T**	**M/O/C**
Controls				
SPCSO	SPC	Single point controllable status output		O
DPCSO	DPC	Double point controllable status output		O
ISCSO	INC	Integer status controllable status output		O
Status Information				
IntIn	INS	Integer status input		O
Alm	SPS	General single alarm		O
Ind	SPS	General indication (binary input)		O

Figure 3.37: IEC 61850-7-4 GGIO LN

XCBR class				
Data Name	**Common Data Class**	**Explanation**	**T**	**M/O/C**
LNName		The name shall be composed of the class name, the LN-Prefix and LN-Instance-ID according to IEC 61850-7-2 clause 19		
Data				
LocKey	SPS	Local operation (local means without substation automation communication, hardwired direct control)		M
RemCtlBlk	SPC	Remote Control Blocked		O
Loc	SPS	Local Control Behavior		M
EEHealth	INS	External equipment health		O
EEName	DPL	External equipment name plate		O
OpCnt	INS	Operation counter		M
Controls				
Pos	DPC	Switch position		M
BlkOpn	SPC	Block opening		M
BlkCls	SPC	Block closing		M
ChaMotEna	SPC	Charger motor enabled		O
Metered Values				
SumSwARs	BCR	Sum of Switched Amperes, resetable		O
Status Information				
CBOpCap	INS	Circuit breaker operating capability		O
POWCap	INS	Point On Wave switching capability		O
MaxOpCap	INS	Circuit breaker operating capability when fully charged		O

Figure 3.38: IEC 61850-7-4 XCBR LN

3.3.5 RTAC Configuration – SEL AcSELerator Architect

The SEL 3555 RTAC configuration is achieved by using SEL AcSELerator Architect and SEL AcSELerator RTAC software developed by SEL ™. The first process involves designing the project file on SEL AcSELerator Architect by importing the CID file from the IED “NewDevice” created previously in the RSCAD Fx ICT configuration. The exported CID file from the ICT tool is saved as “IED1,” as previously discussed in Chapter 2.5; the file-sharing capabilities of devices compatible with the IEC 61850 standard allow exporting and importing configured files across vendors. Therefore, the SEL AcSELerator RTAC software imports the configured data of ‘IED1’ as the configured IED file (CID) encodes that information. Within the SEL AcSELerator Architect platform, the ‘IED1’ and the SEL RTAC are pulled into a single project file. The network settings for each are provided and demonstrated below in Figure 3.39 and Figure 3.40. Note that the network parameters for the ‘IED1’ give the IP address of the GTENTx2 card (192.168.1.206), and the IP address of the RTAC is given as the SEL 3555 RTAC (192.168.1.170).

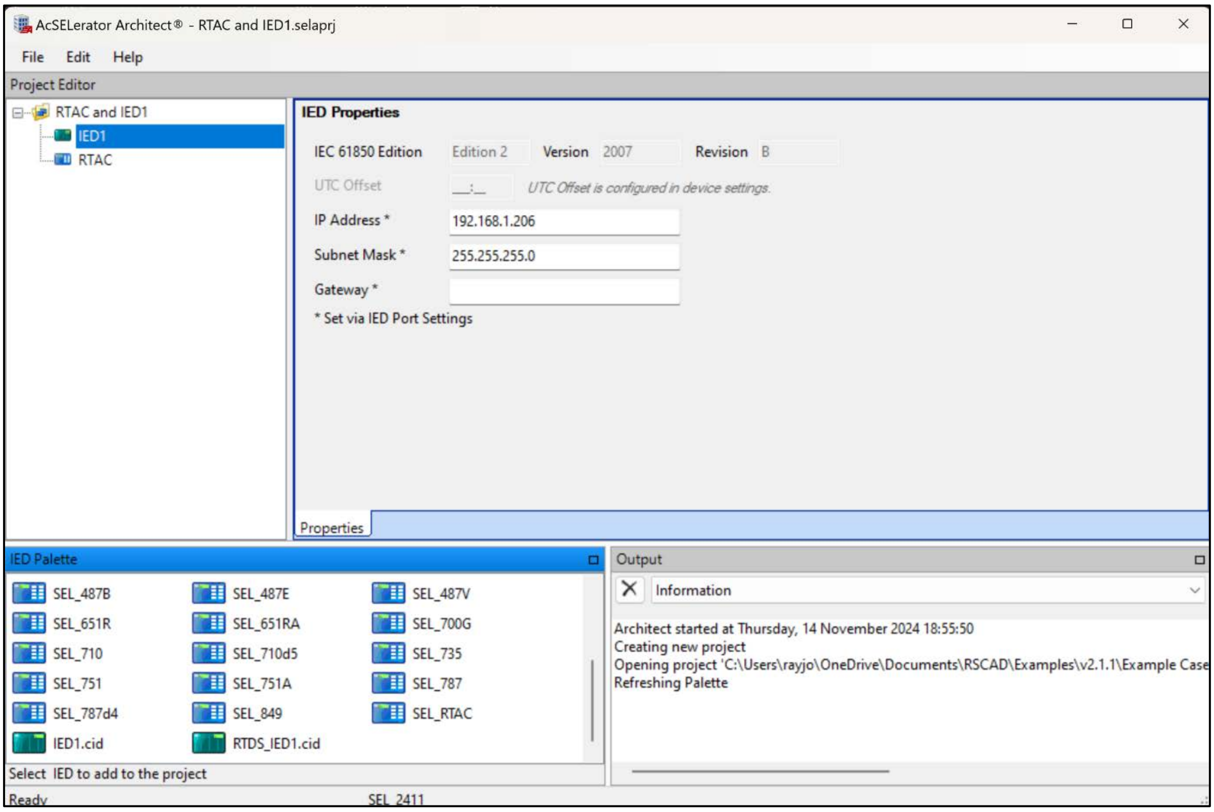

Figure 3.39: SEL AcSELerator Architect – IED1 Network Properties

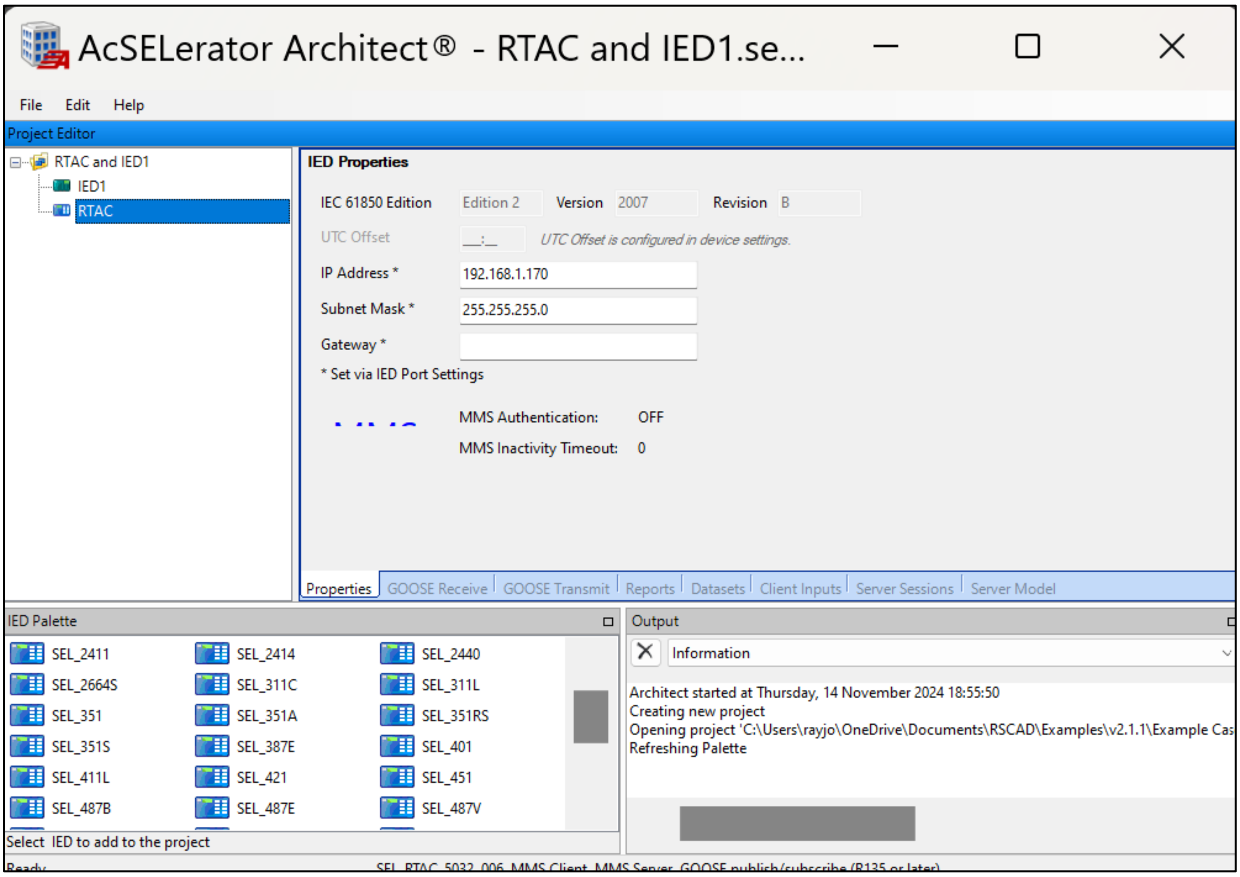

Figure 3.40: SEL AcSELerator Architect – RTAC Network Properties

The RTAC plays the role of the client, and the 'IED1' plays the role of the server. In IEC 61850 MMS, the model requires the client to subscribe to datasets as either polls or reports. Navigating to the 'client inputs' tab of the RTAC shows the datasets provided in the configured 'IED1' list. These datasets are the same as seen in the ICT configuration for the 'Measurements' and 'BreakerStatus' for the polls. The reports are also provided as 'BrkPos' and 'MeasuredVal'. The reports and the polls are pulled into the 'inputs' tab below in Figure 3.40. This concludes the configuration required using the SEL AcSELerator Architect. The project file is saved as 'RTAC and IED1' and be pulled into the SEL AcSELerator RTAC software.

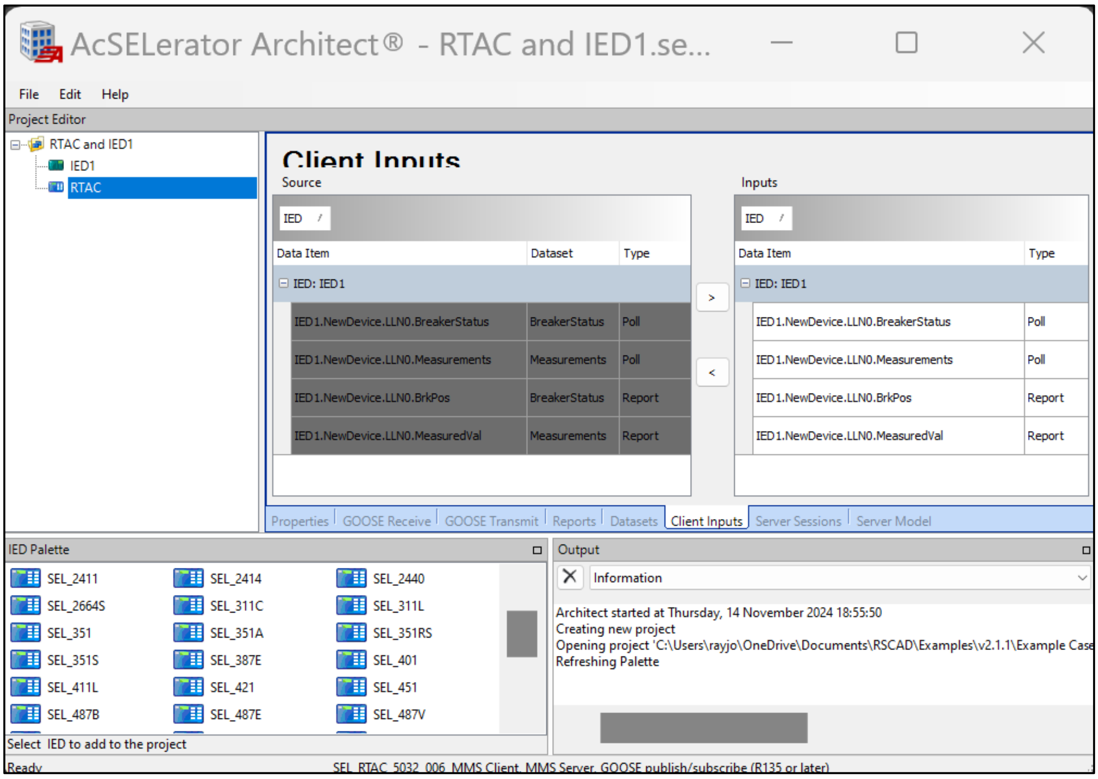

Figure 3.41: SEL AcSELerator Architect – RTAC 'Client Inputs'

3.3.6 RTAC Configuration – SEL AcSELerator RTAC

The project file is exported from the SEL AcSELerator Architect file and imported into the SEL AcSELerator RTAC software. This is achieved by 'importing' and 'IEC 61850 server' in the SEL AcSELerator RTAC software. Once again, the configured project file from the SEL AcSELerator Architect contains the data of the 'IED1' from the ICT software linked with the SEL RTAC. The network configuration reports and polls have already been established. Navigating through the 'IED1' details on the SEL AcSELerator RTAC software shows the configured data in the 'settings' tab, as seen below in Figure 3.42.

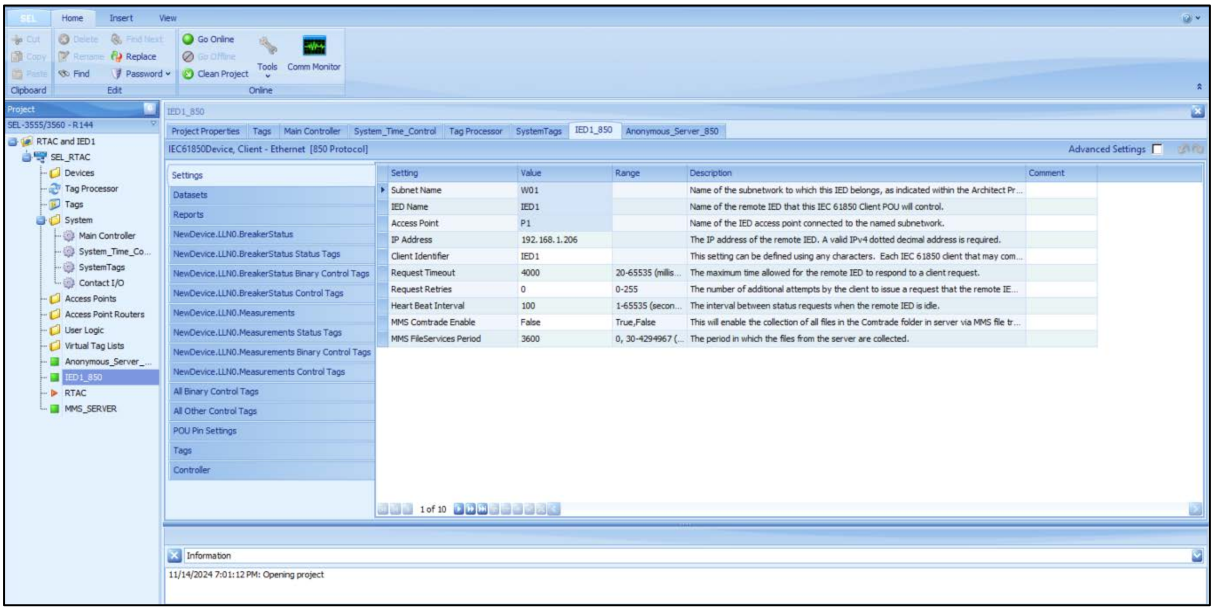

Figure 3.42: SEL AcSELerator RTAC – IED1 ‘Settings’

Navigating the ‘Datasets’ tab of ‘IED1-850’ the polls subscribed to in the SEL AcSELerator Architect project file is displayed and listed below as ‘BreakerStatus’ and ‘Measurements’ as seen in Figure 3.43.

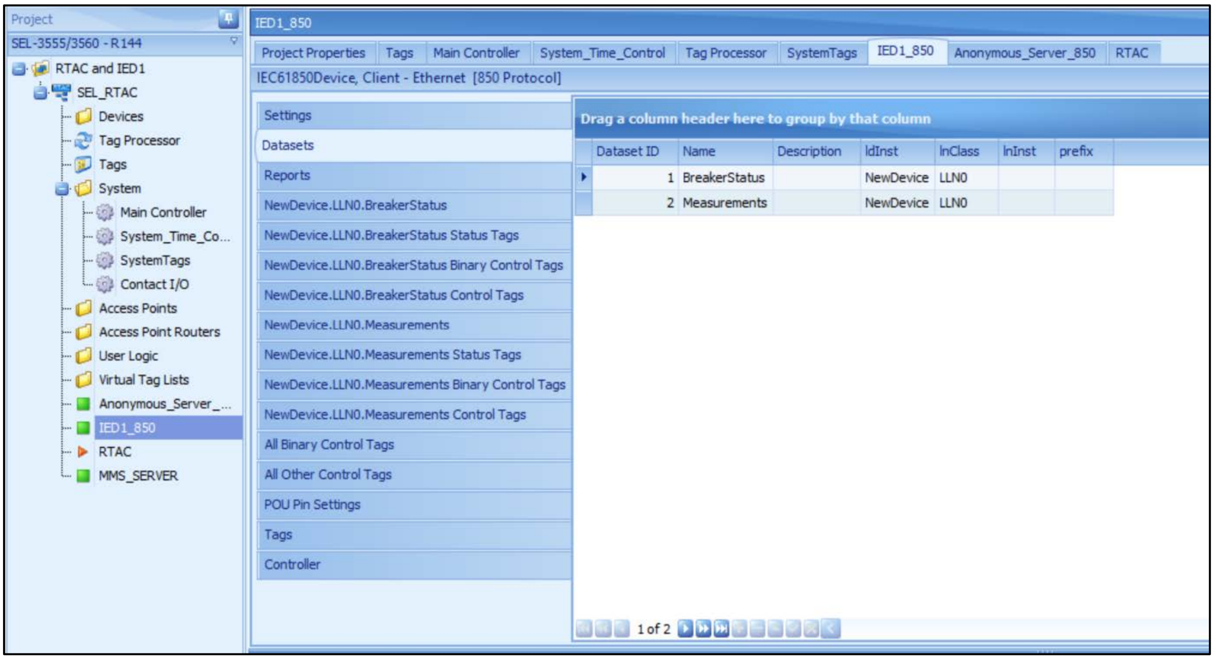

Figure 3.43: SEL AcSELerator RTAC – IED1 ‘Datasets’

The reports are recorded in the ‘Reports’ tab. Figure 3.44 below shows that the SEL RTAC has subscribed to the reports ‘BrkPos’ and ‘MeasuredVal’.

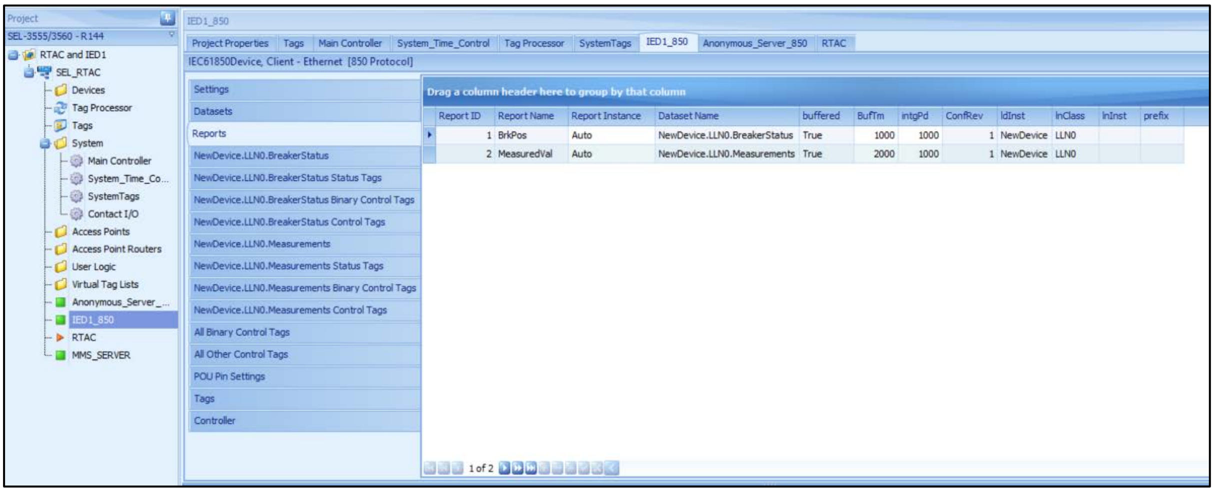

Figure 3.44: SEL AcSELerator RTAC – IED1 ‘Reports’

The breaker status for the LNs ‘LN – XCBR1’ to ‘LN -XCBR5’ are listed under ‘BreakerStatus Status Tags’. The ‘stVal’ are shown with their data type (tag type0 being Double Point Status (as expressed earlier as double bit values).

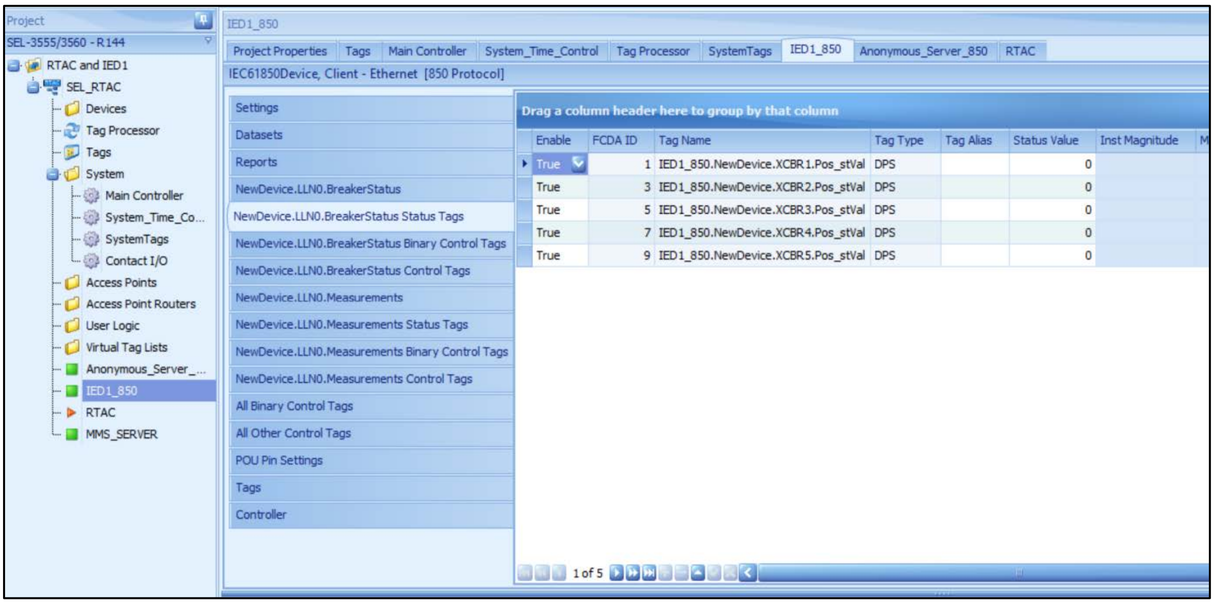

Figure 3.45: SEL AcSELerator RTAC – IED1 ‘BreakerStatus Status Tags’

The status tags for the GGIO logical node configured in the ICT platform for the measurement values are seen under the tab ‘Measurements Status Tags’. The associated data type (tag type) is INS, which, according to IEC 61850-7-3, is an abbreviation for Integer Status data type.

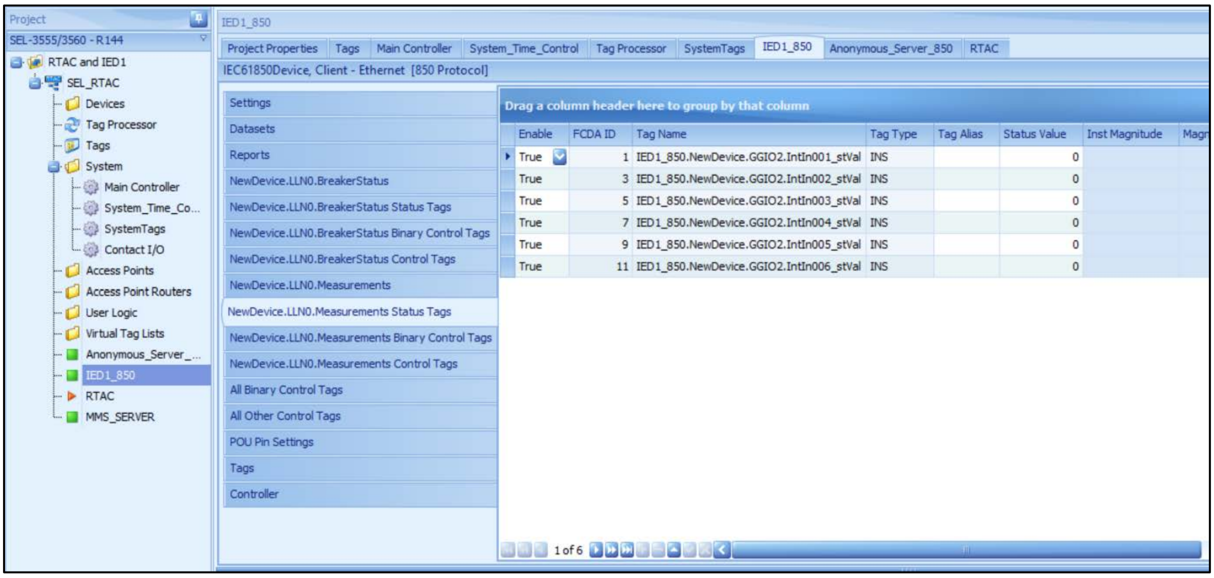

Figure 3.46: SEL AcSELerator RTAC – IED1 'Measurements Status Tags'

The 'Tags' tab of the 'IED1_850' window lists a summary of the tags for both datasets. This provides a single reference point for all the tags that can be monitored and configured in the project file and imported into SEL AcSELerator RTAC. These tags are listed below in Figure 3.47.

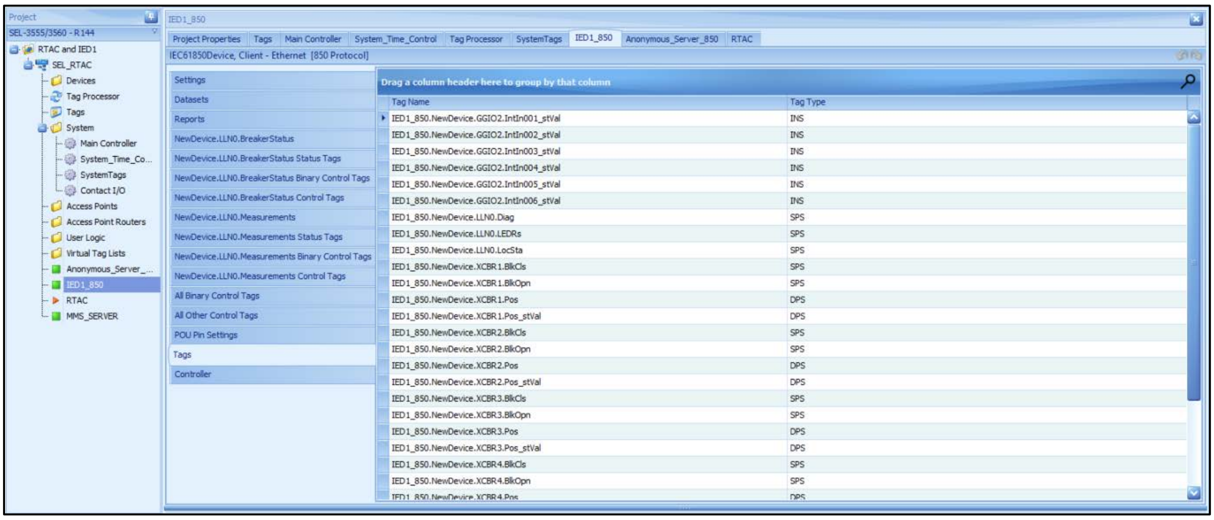

Figure 3.47: SEL AcSELerator RTAC – IED1 'Tags'

3.3.7 RTDS Firmware Configuration and Initialising the Simulation – IEC 61850 MMS

Configuration for the RSCAD Fx components and the SEL 3555 RTAC is complete. Before running the simulation, the firmware configuration for the GTNETx2 cards attached to the RTDS NovaCor must be updated to match the GTNETx2 GSE V7 used in the PPC Interface and configured in the ICT software. As explained in Chapter 3.2.6, the same process is followed, except the firmware selected is the latest GSE version 7.28, as seen below in Figure 3.48.

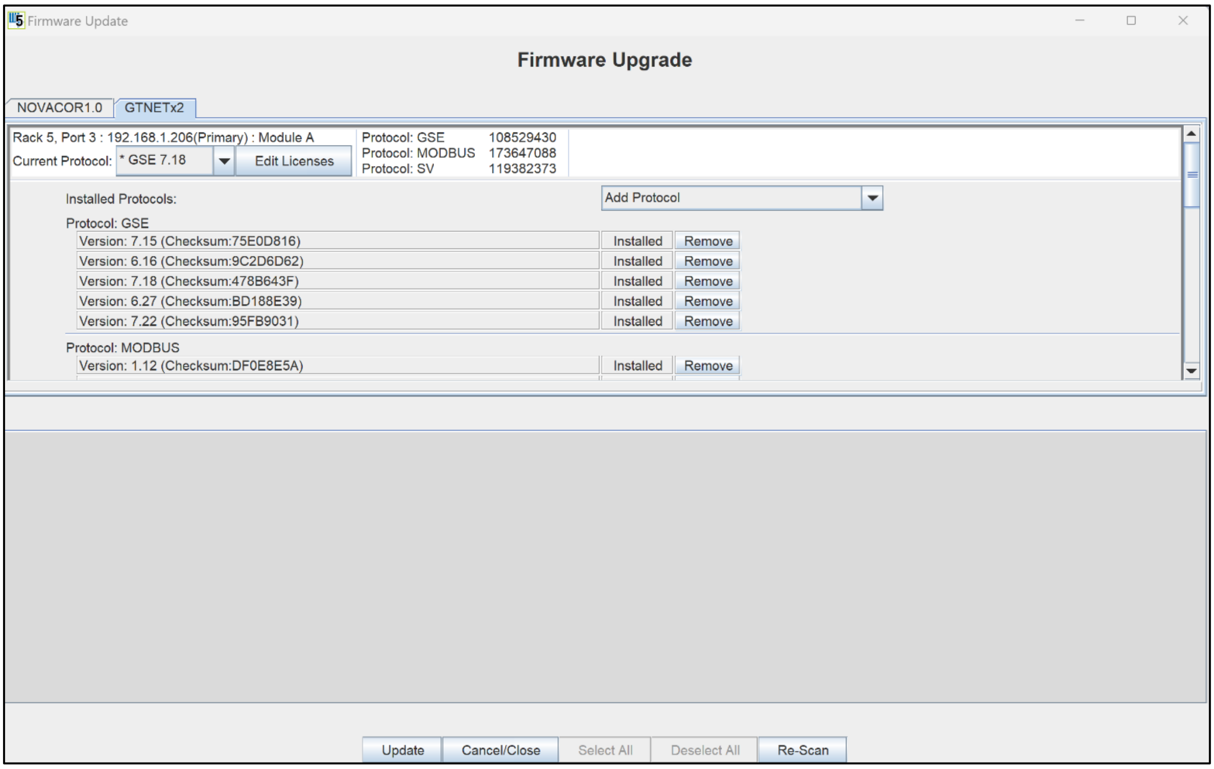

Figure 3.48: RSCAD Fx GSE 7.18 Firmware Utility Upgrade

After the firmware update has been successfully installed in the GTNETx2 card, the RSCAD Fx simulation is ‘compiled,’, and with no errors presented in the message tab, the case is allowed to go ‘life’ by using the ‘run case’ icon.’ This concludes the lab scale implementation configuration of all respective components. This process involves successfully calibrating two simulations, one for Modbus communication and the second for IEC 61850 MMS communication. Both simulations require compatibility from the RSCAD Fx simulation running on the RTDS NovaCor to the SEL 3555 RTAC configured as the PPC. The signal mapping for each protocol displays the difference between the implementation of each protocol. The advantages of using the IEC 61850 MMS protocol have already been noted, such as the detailed implementation of quality bits, timestamping, and reporting.

3.4 Conclusion of Chapter 3

Chapter 3 details the requirements for executing the simulation in the lab provided at Cape Peninsula University of Technicon (CPUT). The lab-scale experiment involves a PV system simulated on RSCAD Fx running on the RTDS NovaCor. The PV system model is kept consistent, but the communication module between the PPC and the simulation is adjusted to match the Modbus and IEC 61850 MMS protocols.

3.4.1 Modbus Implementation

The implementation of the Modbus protocol requires the mapping of signals from the simulation. These signals are listed in Table 3.2 and are grouped by various Modbus registers. Their functionality defines these registered and can often be called function codes. Each vendor has personalized adoptions of these signal registers, so mapping is essential to ensure correct data is being recorded. The PPC is configured as the Modbus client, and the signal is configured to match that of the table recorded in Table 3.2.

3.4.2 IEC 61850 MMS Implementation

Adjusted the simulation from a GTNETx2 card configured as IEC 61850 MMS (GSEv7) is detailed. The communication configuration is completed in a standalone ICT (IED Configurator Tool) software. This process involves data binding logical nodes to a physical device. Then, signals are mapped to data attributes within the LN. Additionally, datasets are developed and used for reports. The reports are defined as buffered and provide higher availability of data. The CID (Configured IED Description) is then exported from the ICT software. This CID file is imported into SEL AcSELerator Architect to create a project file with the SEL 3555 RTAC. Once the reports are subscribed to the project file, they are saved and imported into SEL AcSELerator RTAC software.

3.4.3 Data Capture in Chapter 4

Chapter 4 deals with data capture during the simulation of both instances. The data is captured using the ‘Comms Monitor’ function within the SEL AcSELerator RTAC while the simulation is ‘online.’ The packets are analysed using Wireshark packet analyzer software and IED Explorer. The analysis of the data is based on the findings of the simulation as well as research information expressed in Chapter 2.

Chapter 4: Analysis of Results

In this chapter, both simulations are run identically, and data is captured and analysed to provide a side-by-side comparison of the implementation of either protocol. This research uses the basis of monitoring the simulation as the server providing readings to the SEL 3555 RTAC acting as the client. The two readings are essentially the breaker status positions and measurement values. The RSCAD Fx Runtime window displays a visual reference of the real-time data from the simulations computing in the RTDS NovaCor, and the indications referenced in the Runtime window are verified using the capture packet tool 'Comms Monitor' function in the SEL AcSELerator RTAC software. The 'Comms Monitor' function captures any transmitted data between the GTNETx2 card and the SEL 3555 RTAC. These packet captures are then analysed using the network capture analyzer, Wireshark ™. The comparison of the results is then investigated later in the chapter.

At the end of each lab scale implementation setup during Chapter 3, the RSCAD Fx software is used to initiate the simulation using the 'run case' icon. This initiates the simulation developed on the RSCAD Fx software and various plugin software to go 'live' on the RTDS NovaCor real-time simulator. This real-time data is visually represented on the RSCAD Fx Runtime window. Executing both simulations by entering the same commands entered from the RSCAD Fx Runtime window, the breakers are closed in a succession of MainBrk, PV1DBlk1, PV1DBlk2, PV2DBlk1, and PV2DBlk2. After the breakers are closed, the values are observed using the measured values. These measured values represent the active, reactive, and voltage feedback units from the two PV systems producing power through the HV transformer. These values are adjusted using the Runtime dials to provide Active and Reactive Power Control setpoints.

A summary of Chapter 4 includes the packet capture analysis of the simulation by using the 'Comms Monitor' function within the SEL AcSELerator RTAC software. The comms monitor can only capture data if the project is online. The packet capture provides insight into the data transmitted from client to server in Modbus and IEC 61850 simulations. Additionally, to analyze the data in the IEC 61850 simulation, third-party software called IED Explorer is used to examine the data and datasets. The effectiveness of each protocol is tabulated at the end prior to the conclusion of the chapter.

4.1 Modbus Simulation – RSCAD Fx Runtime

The RSCAD FX executes the Modbus simulation 'run case' icon, and the initial state of the simulation is shown in Appendix A. Systematically, the breakers are closed 'MainBrk', 'PV1DBlk1, PV1DBlk2, PV2DBlk1 and PV2DBlk2. This is seen as the breaker's indication light changes from green to red in the RSCAD Fx Runtime window, as shown below in Figure 4.1.

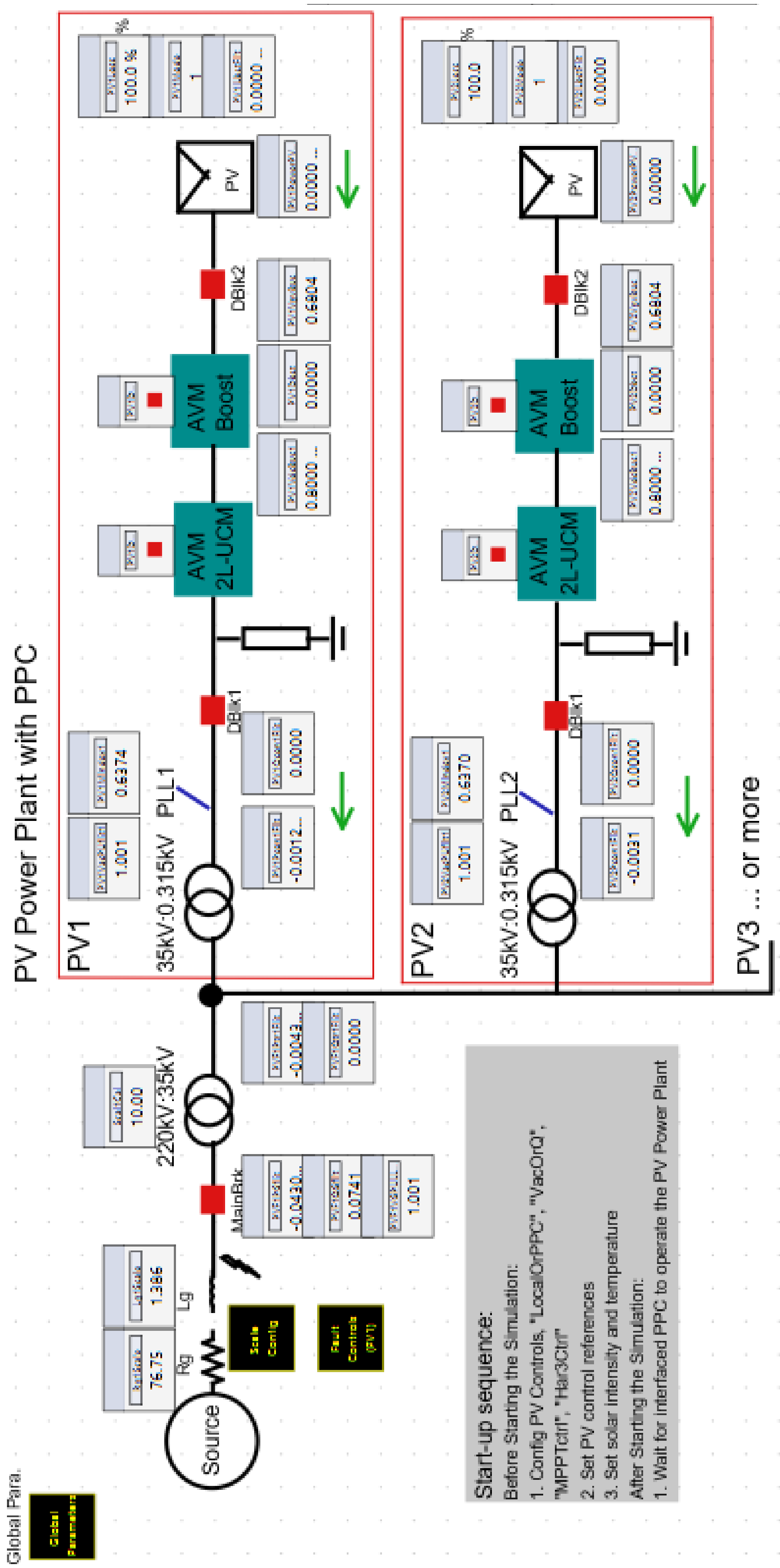

Figure 4.1: RSCAD Fx Runtime – Breaker Closed

4.1.1 Modbus Simulation – Breakers Statuses Wireshark Capture

The Wireshark capture of the breaker status is captured by using the 'Comms Monitor' function of the SEL AcSELerator RTAC software. Any communication transmitted via ethernet ports into the SEL 3555 RTAC is captured and analysed. The initial state of the open breakers can be seen below in Figure 4.2 by noting the bit values of '0' shown in the yellow box with the number '2'. The green box shows that the communication is coming from IP address 192.168.1.206 (GTNETx2 card of the RTDS NovaCor), and the destination IP address is indicated in a red box showing the IP address 192.168.1.170 (SEL 3555 RTAC). The yellow indication box labelled '1' shows that the function code is 2, 'Read Discrete Inputs.' Noting the signal list established in Chapter 3.2.4 the mapping of Bit 0 = PV1DBlk1, Bit 1 = PV1DBlk2, Bit 2 = PV2DBlk1, Bit 3 = PV2DBlk2 and Bit 4 = MainBrk. It is noted that the response containing the data for the discrete inputs comes after being initiated from a 'Query' from the SEL 3555 RTAC; this is the Modbus Client polling data at defined intervals. The 'Response' by the server provides data related to the query received.

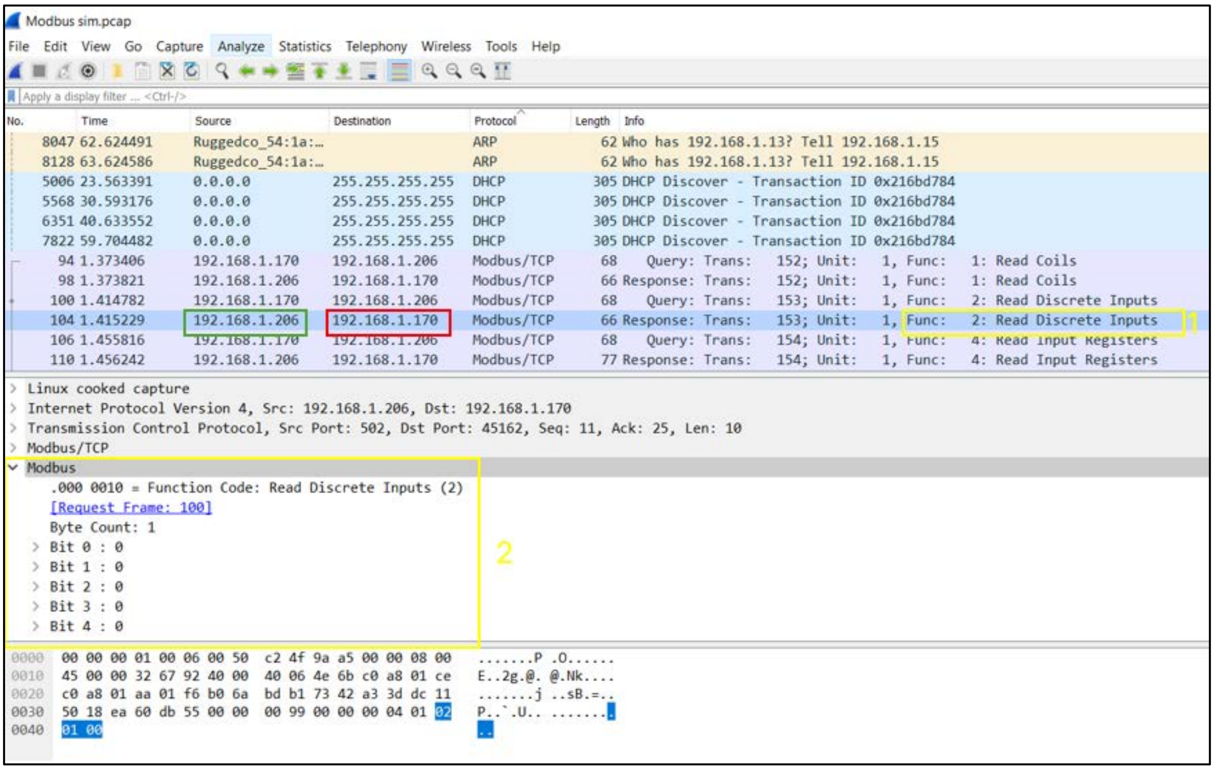

Figure 4.2: Modbus Wireshark Capture – Breakers Open

A packet captured later shows Bit 4 = 1, noting that the 'MainBrk' has changed states from being open to closed. This confirms the signal mapping in Chapter 2.3.4 is correct, as the breakers are closed systematically from MainBrk during this simulation. Therefore, noting that Bit 4 changed with other breakers remaining in their initial state is expected. This is displayed in the Wireshark capture of Figure 4.3 below.

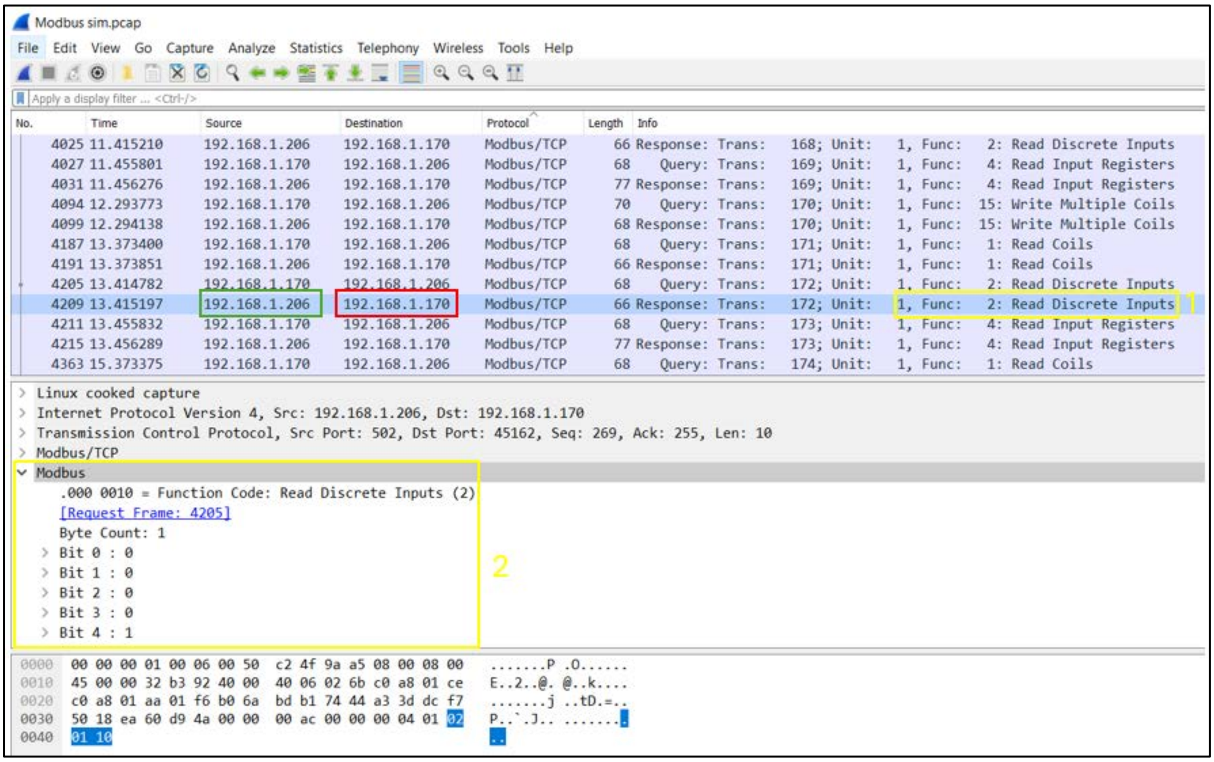

Figure 4.3: Modbus Wireshark Capture – MainBrk Closed

The third and final capture of the breaker statuses shows all five bits with the value of ‘1’, indicating that they are all closed. This in the Runtime window, as seen in Figure 4.4, with all breakers displayed with red indication lights.

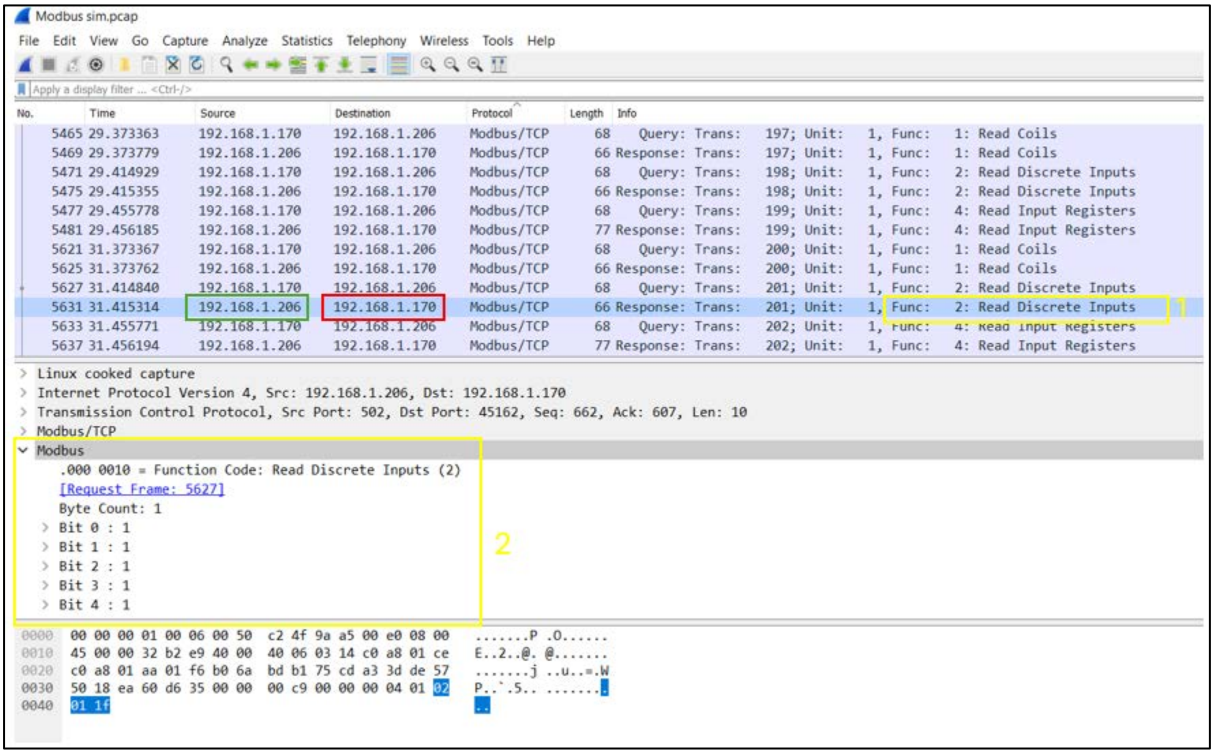

Figure 4.4: Modbus Wireshark Capture – Breakers Closed

The status of the circuit breakers can also be verified by looking at the SEL AcSELerator RTAC software, which is busy running ‘online’. The tags previously expressed in Chapter 3 now contain statutes based on real-time data shared between the RTDS NovaCor and the SEL RTAC. These tags for the Modbus input registers are Boolean logic and change between ‘FALSE’ (open) and ‘TRUE’ (closed). An extract of monitoring these tags for the breaker statuses can be seen in Figure 4.5 below.

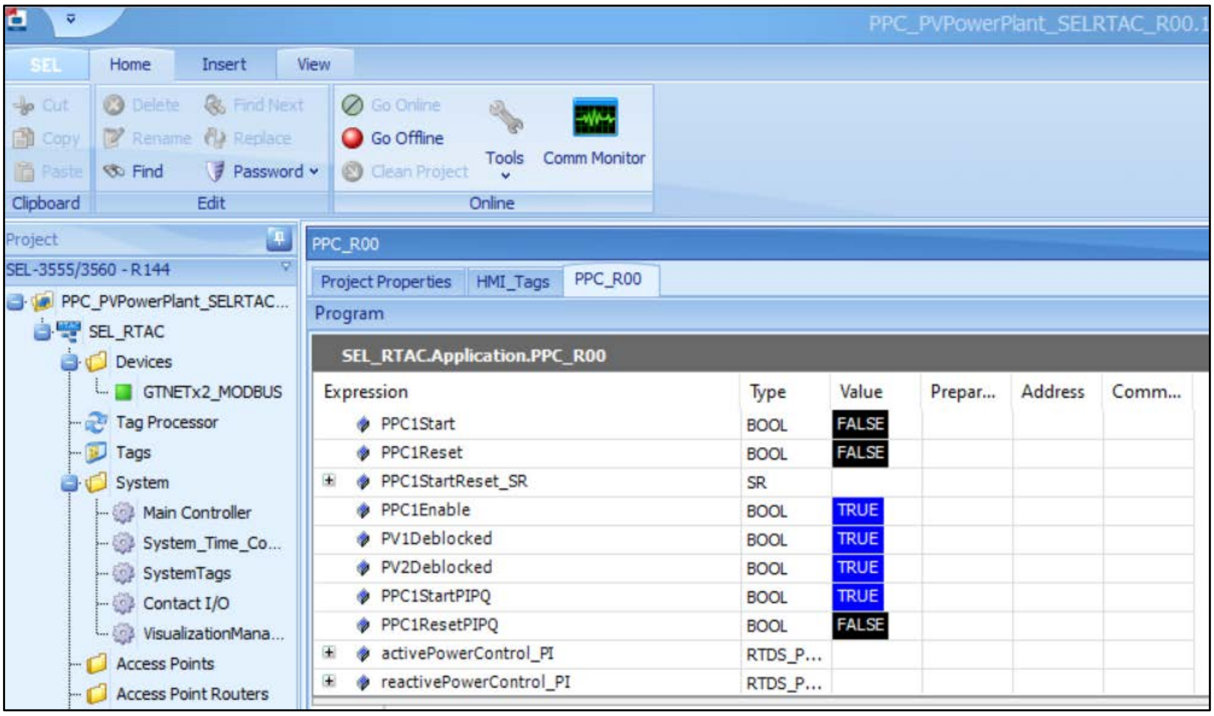

Figure 4.5: Modbus SEL RTAC Real-Time Tags – Breakers Closed

4.1.2 Modbus Simulation – Input Registers Wireshark Capture

The function code 4 for input registers contains the data regarding the measurements mapped in the Modbus Signal List table. Figure 4.6 shows the Wireshark capture of the response to the Read Input Registers query from the SEL RTAC. The purple indication box labelled 1 state that the function code for read input registers is 4, and the second purple indication box labelled ‘2’ shows each of these registers as listed in the Modbus Signal List table. From the previous signal mapping seen in Table 3.2, the Modbus Input Registers are mapped as unassigned 16-bit registers. Registers 0 and 1 are combined for signal PVF1PGPUfilt. Registers 2 and 3 are combined to form signal PVF1QGPUfilt. Lastly, registers 4 and 5 are combined to form signal PVF1GPULLrmsFilt. In the RSCAD Fx simulation these values are continuously fluctuating and can be seen represented graphically in Appendix D. Note the PPC Plots in Appendix D as the graphs display a range of each input register received from the RTDS NovaCor that is being translated into unassigned 16-bit registers read in the Wireshark capture.

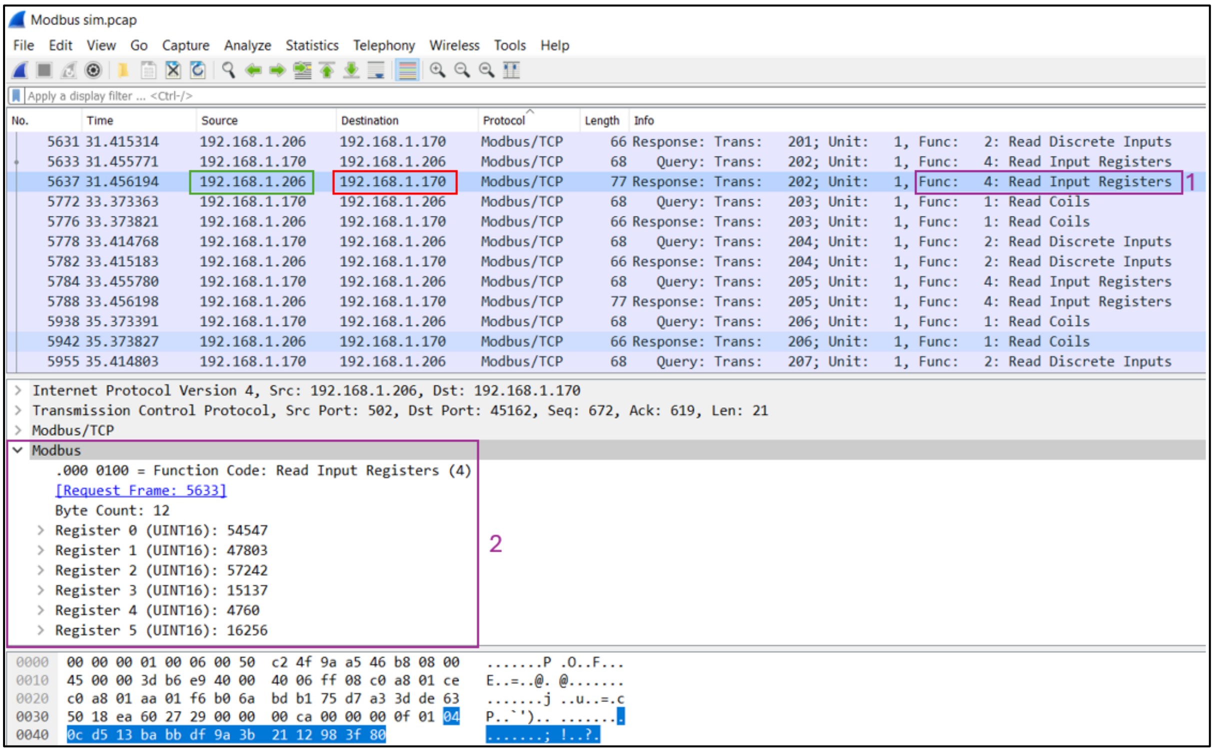

Figure 4.6: Modbus Wireshark Capture – Breakers Closed

4.2 IEC 61850 MMS Simulation – RSCAD Fx Runtime

As with the Modbus simulation, the IEC 61850 MMS project is compiled and run using the RSCAD Fx software. Successful compilation means the run case is loaded onto the RTDS NovaCor for real-time data processing. The initial state of the circuit breakers is returned to the open position, as seen in Appendix A. The same step-by-step execution of the simulation as achieved in the Modbus example is implemented. They are closing breakers sequentially from MainBrk to PV2DBlk2 and using the 'Comms Monitoring' tool as part of the SEL AcSELerator software to capture ethernet data being exchanged between the RTDS NovaCor and the SEL 3555 RTAC.

It can be noted by monitoring the tags on the SEL AcSELerator RTAC software that the quality bits change from 'invalid' to 'good' once the simulation from RSCAD Fx draft is 'live' and the project on the SEL AcSELerator RTAC is 'online'. The change in quality bits is referenced below in Figure 4.7 using LN XCBR2 for demonstration. It is noted that the breaker 'stVal' is still in 'dbpos_intermediate_state' (double bit position intermediate = 0 0) and can be noted as open.

Figure 4.7: MMS RTAC Tag – XCBR2 Quality Bit 'good'

4.2.1 IEC 61850 MMS Simulation – Breakers Statuses Wireshark Capture

The network packet analyzer Wireshark is used to interpret the data captured in the 'Comms Monitoring' tool of the SEL 3555 RTAC. The data exchanges related to the circuit breaker positions are examined below in Figure 4.8. Once again, the green and red indication boxes highlight the IP addresses of the GTNETx2 card and SEL 3555 RTAC, respectively. The yellow indication box highlights an unusual occurrence, stating that there has been a protocol data unit (PDU) request. Looking at the data interpreted in the black indication box shows that the request is the 'Client' (SEL RTAC) asking for information regarding the device called 'IED1NewDevice' to provide data regarding the 'BreakerStatus' datasets in the common logical node zero (LLNO). It must be noted that IEC 61850 MMS protocol is not a default protocol that is analysed in the Wireshark preferences and must be added by navigating to 'Preferences, Protocols, PRES' and adding the protocol identifier code 1.0.9506.2.1 to decode the encapsulated data.

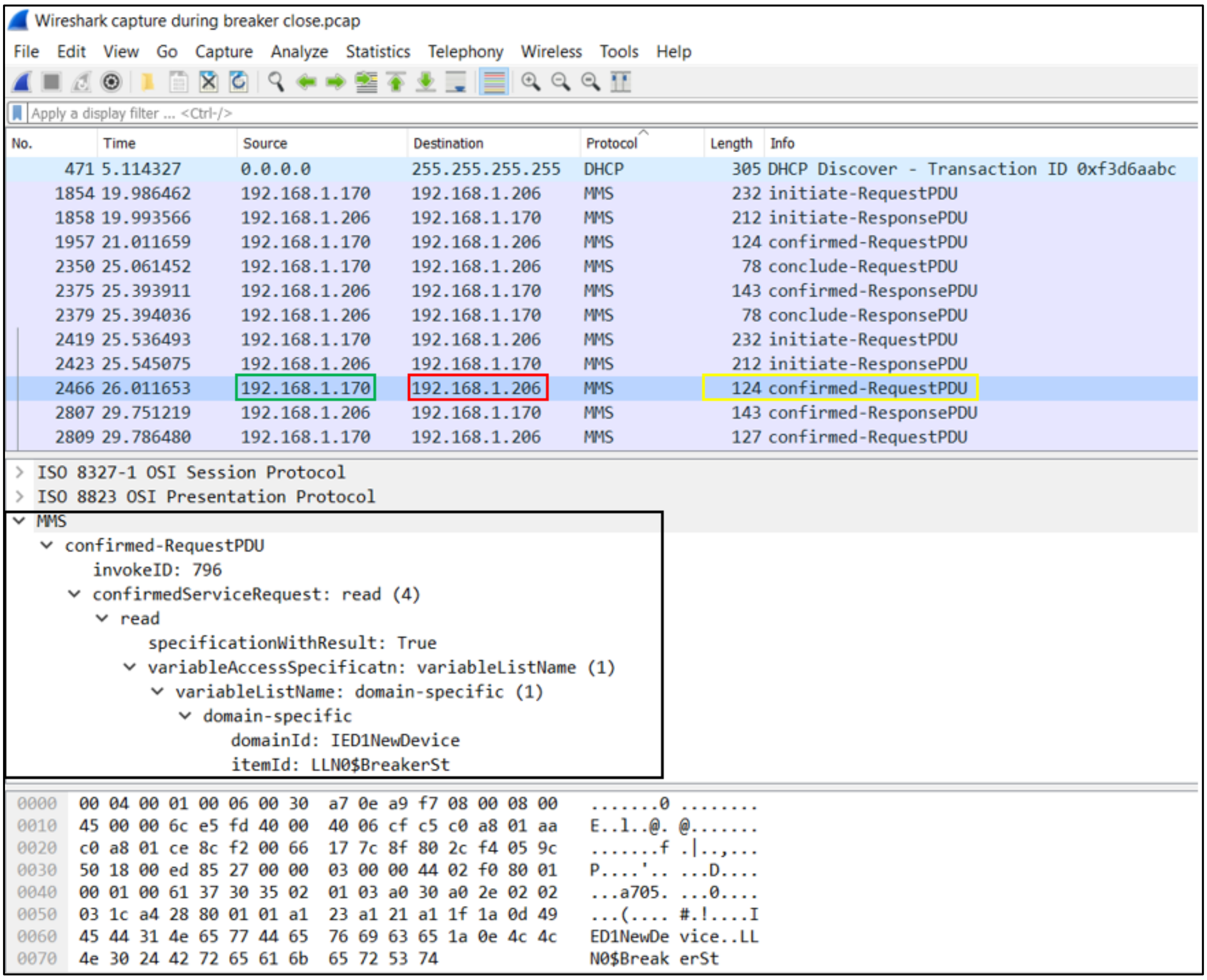

Figure 4.8: MMS Wireshark Capture – BreakerStatus Query

Figure 4.9 shows the server's response, the RTDS GTNETx2 card, to the query requested by the SEL RTAC. Similar indication boxes highlight specific data of interest.

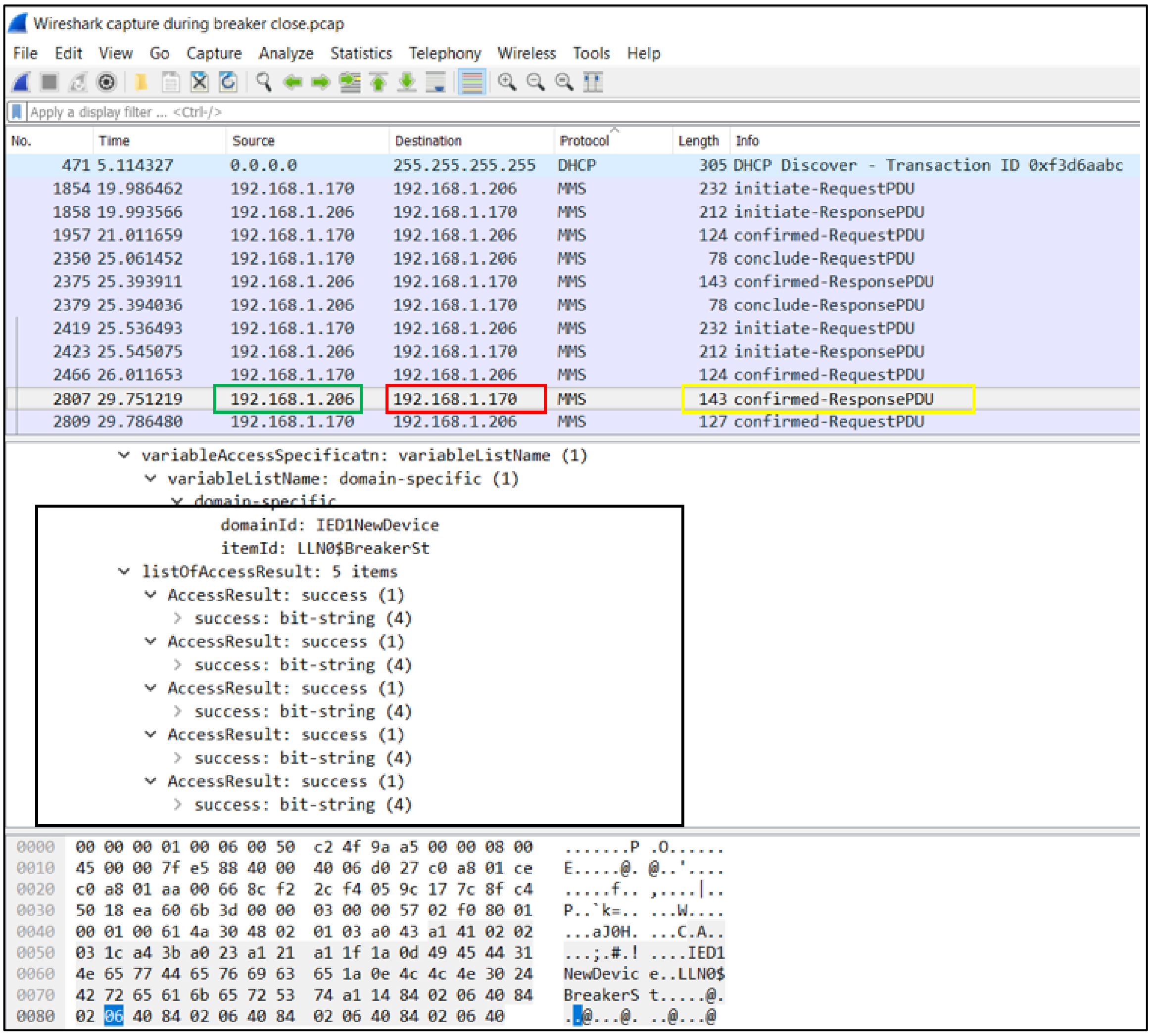

Figure 4.9: MMS Wireshark Capture – BreakerStatus Response

After the breakers are closed, another method to verify the state other than using the RSCAD FX Runtime window to confirm the data represented matches the data captured in the packets is to monitor the tags in the SEL AcSELerator RTAC software, as seen in the introduction of this subsection. The change of state from breaker 'stVal' can be noted as 'dbpos_off' (double bit position off = 0 1). This state change is misleading as the SEL RTAC reads the DPS 01 as 'off,' whereas, in the simulation, it corresponds to 'closed.' Configuring these DPS to align is essential to ensure data is understood correctly. This would require additional programming in the SEL 3555 RTAC to manipulate the logic behind the data it receives or look at the configuration from RSCAD Fx to see how the MMS data is mapped for DPS. This is referenced below in Figure 4.10.

Figure 4.10: MMS RTAC Tag – XCBR 'stVal' Breaker Closed

4.2.2 IEC 61850 MMS Simulation – Measurements in Wireshark Capture

The second capture focuses on obtaining data related to the ‘Measurement’ datasets. The query from the client requests the data from the server. This is seen in Figure 4.11 below.

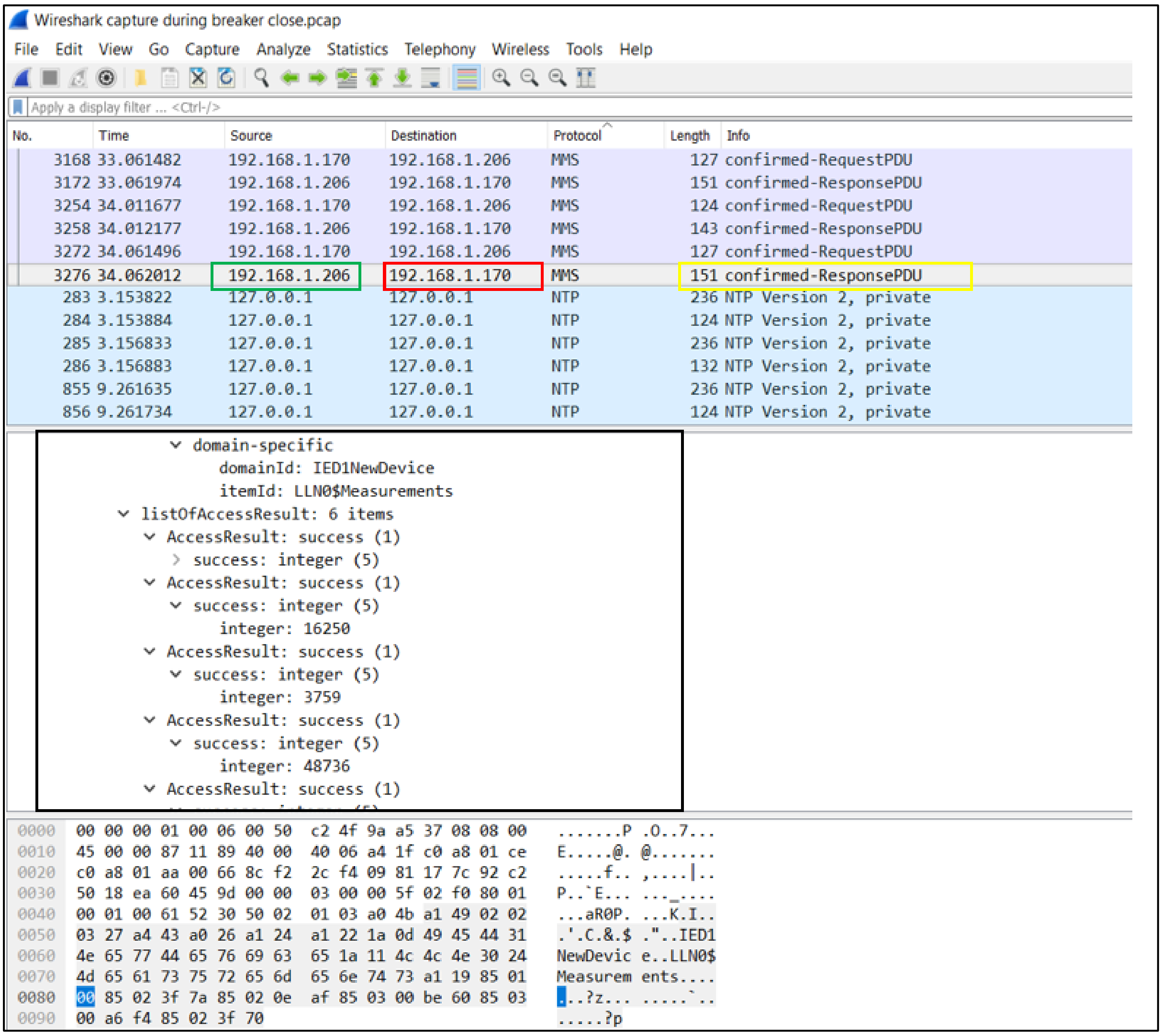

Figure 4.11: MMS Wireshark Capture – Measurements Response

The data can also be monitored live from the SEL AcSELerator RTAC software. This shows the values captured in these data transmissions between the RSCAD Fx simulation and the SEL 3555 RTAC. Figure 4.12 below shows the monitoring of LN GGIO2, IntIn003 data. The highlighted box encapsulates the integer value and the quality bit. Reference to the ICT mapping for the signals to their respective GGIO IntIn (integer inputs) DO’s is completed in Chapter 3.3.4. Here the real-time values are referenced to Appendix D, specifically focusing on the highlighted window “PPC Plots”. This window displays the values sent from the RTDS simulation to the PPC for power quality measurements. An additional software called IED Explorer is used as data validation and is discussed in the following Chapter 4.2.3.

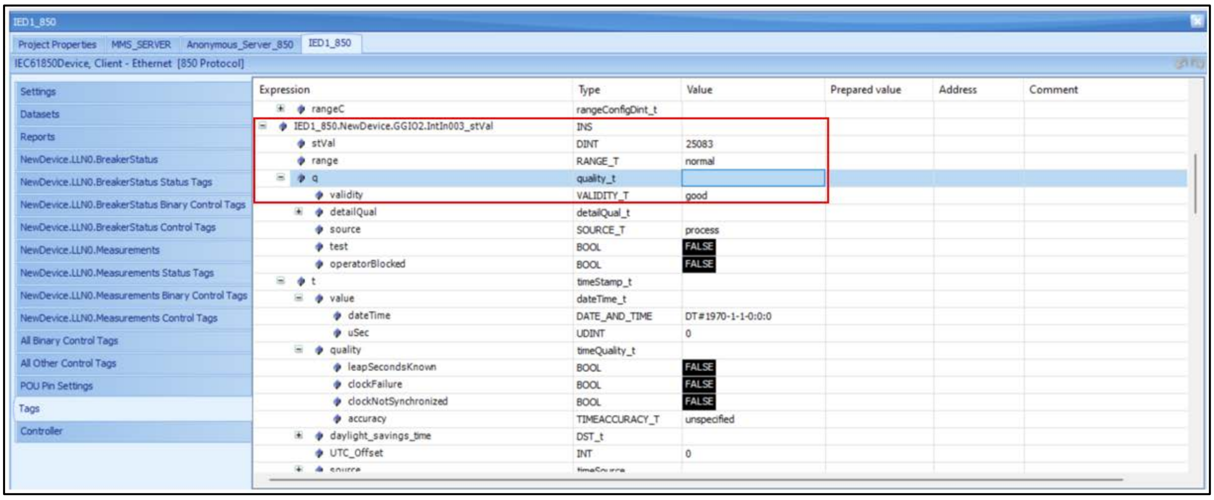

Figure 4.12: MMS RTAC Tag Monitoring – Measurements GGIO

4.2.3 IEC 61850 MMS Simulation – Data Validation

Utilizing various tools and verifying the data represented in the SEL RTAC is possible. As a built-in function under Protection and Automation Utilities in RSCAD Fx suite is provided an extension called MMS Voyager. This standalone program acts as an IEC 61850 client designed to communicate with IEC 61850 server devices. The IEC 61850 server device data is pulled into the MMS Voyager program by importing the IED file developed in the ICT configuration "IED1". MMS Voyager then enables the functionality to poll data based on available data attributes stored in the CID file of "IED1". Polling data attributes of the breaker statuses and the measurement values allows the cross-reference between the data presented in SEL RTAC to be verified.

A third-party, open-source software, 'IED Explorer' is used to validate the data and MMS Voyager. Once the IED Explorer has scanned the IP address, it can present data, as seen in Figure 4.11 below. The expanding tree format of the data shows that the path to data attributes is established through defined logical nodes in the logical device. This is a standard method of presenting data for the IEC 61850 communication standard, as these pathways are standardized for each data attribute. The logical device is recorded as "IED1NewDevice," and underneath the logical device are listed Logical Nodes identical to the ones developed in the ICT program of RSCAD Fx. Furthermore, the Logical Device lists datasets and Buffered Reports derived from configuring the virtual IED within RSCAD Fx. The Logical Nodes, Datasets and Buffered Reports are indicated in Figure 4.13 with red, green and blue indication boxes. Expanding the data of the 'BrkPos' buffered reports shows the configuration related to the buffered report. Noting the buffered time is equal to 1000 milliseconds.

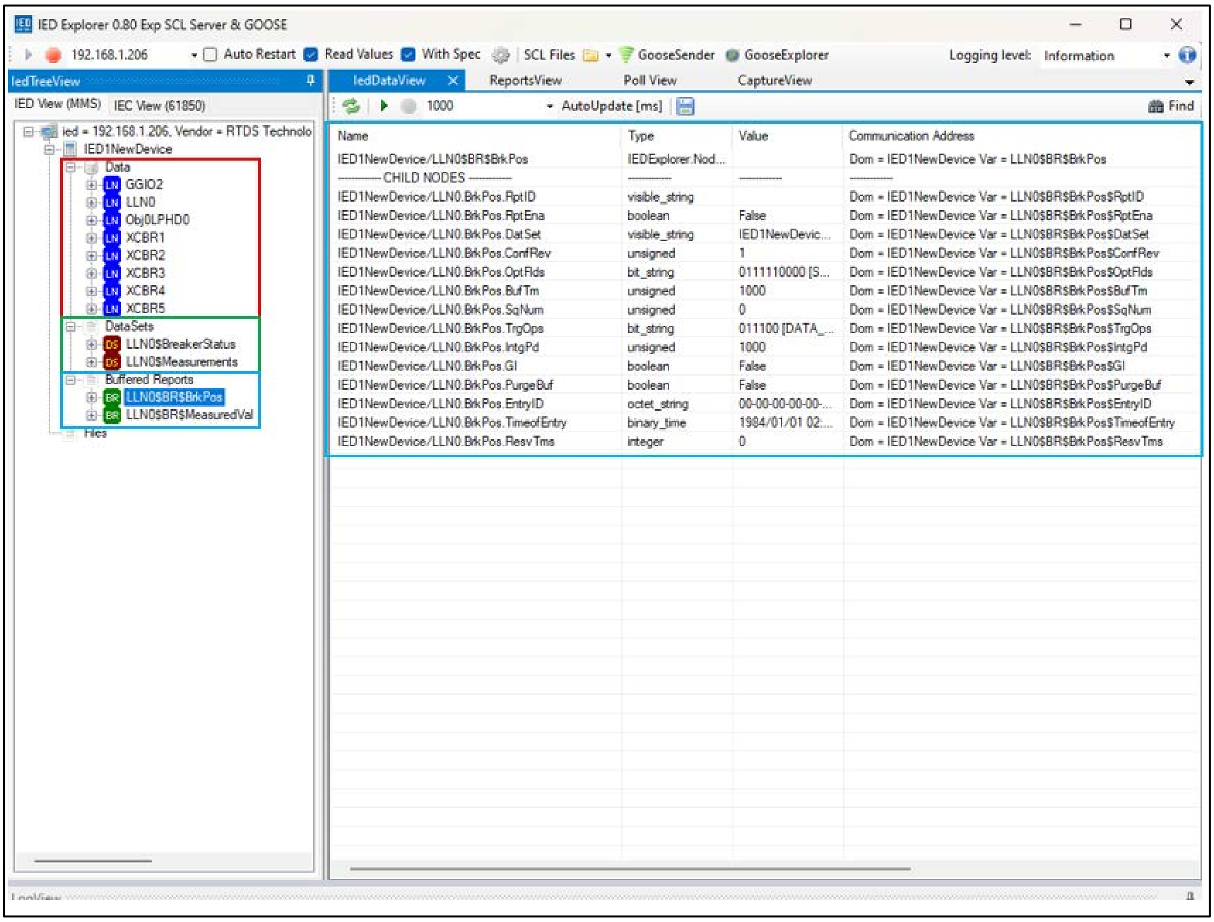

Figure 4.13: IEC 61850 Validation: IED Explorer 'BrkPos'

The data can be viewed simultaneously using the SEL RTAC, MMS Voyager, and IED Explorer as a reference across all three programs. Ensuring consistency across all three programs validates the data presented. The DPS value must be consistent across the programs for breaker positions, as seen below in Appendix B for breakers in the closed position. The breaker statuses are highlighted using red indication boxes showing the breaker position and respective quality data.

4.3 Comparison of Simulation Results

The results have been captured, and data is now present to run investigations. This section uses the data to study advantages, disadvantages, and advanced features and creates a comparison between them.

This section studies the data captured in Wireshark transmitted between the RTDS NovaCor simulation and the PPC. In Modbus protocol, the data studied is placed within the registers Discrete Inputs and Input Registers. For IEC 61850 MMS, the data studied is classified by LN and datasets. The speed of query and response time is calculated using the third-party software IED Explorer.

4.3.1 Analysis of Modbus Simulation

The Modbus simulation is executed by creating a signal list based on the data transmitted in each function code (register). The signal list is identified from the RSCAD GTNETx2 Modbus manual to identify registers available. Compiling the GTNETx2 Modbus component in RSCAD Fx is relatively simple as the process involves tabs for each data required per register. An additional tab for the network parameters established the IP settings of the GTNETx2 card. Monitoring the transmitted data using SEL RTAC 'comms monitor' to generate packet capture (pcap) files viewed in Wireshark. The data for circuit breaker positions is presented as Boolean logic and listed per the signal list developed. A similar experience is noted with the integer values for the Input Registers. On Wireshark, it is possible to see the description of the query and the response as indicated for Discrete Inputs and Input Registers. Subsections of this chapter specifically break down the capabilities and data interpretation for the effectiveness of utilizing the Modbus protocol.

4.3.2 Modbus Functionality

The Modbus functionality can be observed by looking at the protocol's capabilities. It is noted in Chapter 2.3 that Modbus works based on a Master/Slave or Client/Server relationship. The Modbus application data is encapsulated in TCP/IP protocol when distributed over a network; otherwise, Modbus RTU can be implemented. The development of Modbus to become vendor-specific resulted in multiple versions. However, the working principle remains consistent. Data is categorized by registers called function codes, which have defined functionality associated with read or write privileges.

4.3.3 Modbus Packet Capture Analysis

Wireshark captures packets transmitted between the RTDS NovaCor simulation and the SEL RTAC, acting as the PPC displayed in Chapter 4.1, to assist with decoding and debugging data. The default settings of Wireshark decode the Modbus protocol data and describe the query type and response. Query response with breaker status used 66 bytes of data and listed the simply in register format from Bit 0 to Bit 4. The breaker positions are reflected by Boolean logic: 0 is open, and 1 is closed. The Modbus data captured for the Input Registers for the measurement data is very similar. The register format lists the values from 'Register 0' to 'Register 7' with the associated data type, 'UINT16' (unsigned 16-bit integer), before the respected values are provided. It is noted that the reading of input registers is 77 bytes in total. The time taken to respond to a query for the Discrete Inputs and the Input Registers. The Discrete Inputs can be determined by taking the recorded time for the response on line 5631 as 31.415314 seconds and subtracting the recorded time from the query in line 5627 as 31.414840 seconds. The delta time is noted as (31.415314s - 31.414840s) 0,000474 seconds. These values are presented in Figure 4.2. Repeating this investigation for the difference in the time for Input Registers can be recorded by taking the time noted for the response on line 5637 at 31.456194 seconds and subtracting the time recorded for the query on line 5633 at 31.455771 seconds. This delta time between the responses is (31.456194s -31.455771s) 0.000423 seconds. Both reactions are less than half a millisecond delay from the query.

4.4 Analysis of IEC 61850 MMS Simulation

To implement the IEC 61850 MMS protocol, the GTNETx2 GSEv7 configuration using the ICT tool requires more input from the user.

4.4.1 IEC 61850 MMS Functionality

The functionality of the IEC 61850 MMS protocol is examined by noting the composition required for data mapping, explained in Chapter 2.4 and implemented in Chapter 3.3. The development of the IEC 61850 standard has been curated towards fulfilling the requirements experienced explicitly in the electricity and power industry. The standard allows for modification so that future developments may be quickly adopted. The implementation of (logical tree expansion) allows for Logical Nodes to be created that hold specific functionality, as seen with the progressive IEC 61850-7-420 standard for DERs. Further development of these Logical Nodes can continue to improve the standard as future developments occur. The Logical Nodes expand, providing a list of Data Objects. These Data Objects contain Data Attributes. Depending on their associated data type, these attributes contain data that can be read or written. Data types for single-bit logic include single point status (SPS) for read-only and single point control (SPC) for read-and-write functionality. The IEC 61850 also includes double point status (DPS), a combination status of 2-bit logic for read functionality. The read-and-write functionality of a double-bit data type is called DPC. This provides four possible configurations that can give more information regarding the statuses compared to the two possible configurations with single-bit logic (Boolean). Additional functionality embedded in the IEC 61850 standard is the use of the quality data object. The quality data object comprises a byte (8 bits) of information. To establish 'good' quality, the data represented in all 8 bits of the quality must be in state '0', as referenced in the literature review for the IEC 61850. The quality bits that present status '1' indicate the error resulting in bad/invalid quality for communication between devices.

4.4.2 IEC 61850 MMS Packet Capture Analysis

Referencing the packet captures analysed in Wireshark during Chapter 4.2, the MMS communication data is interpreted for a comparison study between the data captured for Modbus communication, as discussed in Chapter 5.1 above. It is noted that even after adding functionality for the protocol identifier of MMS for Wireshark, the data analysis does not reflect the expected details. The details provided in the 'info' tab of the Wireshark window show that there is either a request or response PDU (protocol data unit), but it does not elaborate further. Concerning Figure 4.8, expanding the data provided for each communication provides the detail 'domainId: IED1NewDevice' that lists the device's name responding. Further down the list the 'itemId: LLN0$BreakerSt$' defines the dataset that the data is relevant to. This 'request' from the SEL RTAC is asking for the statuses of the breakers; the response seen in Figure 4.9 shows the list of data but does not indicate the DPS status. This seems to be an error when processing the MMS data from Wireshark, and even after adding the protocol identifier code, the syntax is unclear. Therefore, debugging and troubleshooting are suggested to be completed using the other validation tools in Chapter 4.2.3. The third-party software 'IED Explorer' shows the data configured in the CID file, listed as the typical IEC 61850 standard format. From the packet captures it is possible to note the length of the packets used for data transmission for both breaker statuses and measurement values, as indicated in Figures 4.9 and 4.10, respectively. The response length for the breaker statuses is 143 bytes, and the length for the measurement integer values is 151. The query response speed is also calculated for breaker statuses as T1 = 25.061452 and T2 = 25.393911; therefore, delta T = T2 -T1 = 0.332459 seconds. A similar approach is taken to determine the response time for the measurement data T1 = 34.061496 and T2 = 34.062012; therefore, delta T = T2 -T1 = 0,000516 seconds.

4.4.3 IEC 61850 MMS Validation Analysis

Chapter 4.2.3 verifies data validation using third-party software, 'IED Explorer', and the standalone MMS Voyager program. Referencing the statuses of the breaker position in closed and open, it is noticed that the DPS has been mapped unusually from the RTDS 'IED1' server. RSCAD Fx has encoded that breakers in the open position contain a DPS value of '00' and closed breakers contain the bit data '01'. This results in the notes of the SEL RTAC tags to monitor these DPS incorrectly. The quality bit is noticed clearly in the IED Explorer and MMS Voyager, showing '0' bits in all eight placeholders when the communication is successful.

4.5 Comparison Analysis

Table 4.1: Modbus vs IEC 61850 MMS Comparison Analysis

Criteria	Modbus	IEC 61850 MMS
Signal Mapping	Simplified – signals are categorised by their functionality or function code.	Complex mapping – involves assigning defined LN created for specific use cases.
Data Types	Basic – single bit Boolean, integers and floats	Advanced – SPS, SPC, DPS, DPC, integers, floats
Availability of data	Moderate – no advanced features for ensuring data transmission	High Availability – reports can be configured as buffered and ensure a waiting period if the recipient device is unavailable momentarily
Data Presentation	Raw data is matched to a register	The abstract syntax allows more straightforward interpretation of data
Responsiveness	Data is polled on a time interval.	Data can be polled. Reports can be configured when a change of data occurs.
Response Time	Fast	Fast but marginally slower than Modbus
Data Payload	Minimal	Slightly heavier
Interoperability	non	Extensive
Relative	It is an outdated protocol but familiar and has been used successfully for decades	Modernized developments for future expansion.
Timestamped	Not available	Available
Quality Check	Not available	Available

4.6 Conclusion of Chapter 4

4.6.1 Conclusion of Modbus Data Analysis

The data captured in the Modbus simulation is analysed using Wireshark packet capture software. The interpretation of the data is clear, and the description of the request or responses is provided. The data concerning the signal list must be read as a guide. The response to the queries is fast, and the data payloads are low for data transmission.

4.6.2 Conclusion of IEC 61850 MMS

Viewing the data captured in Wireshark shows the expanding-tree format employed by the IEC 61850 standard. The data is presented based on logical nodes and datasets. Due to the abstract syntax, the data is legible without reference to a signal map. Additional software called IED Explorer is used to verify the data and configuration of the IED configured for the RSCAD Fx simulation.

4.6.3 Conclusion of Comparative Analysis

The comparative analysis investigates the difference between the implementation of the two protocols. These differences are then tabulated and summarised in Table 4.1. This table notes various features the IEC 61850 MMS protocol provides unavailable in Modbus. The advantages provided by implementing the IEC 61850 MMS protocol provides a strong case for the protocol being better suited for the application of inverter communication to a PPC.

To ensure that the data transmitted from the RTDS simulation and received by the PPC without any errors it is important to ensure data validation is implemented. This is achieved through the simulations by analysing the data captured in Wireshark and comparing it to the values noted in the Runtime live view of the RTDS versus the data displayed in the tags of the SEL 3555 RTAC once the project is online. It is during this project being online that the 'comms monitor' tool of the RTAC is used to capture packets that is then analysed in Wireshark, once again to validate that data being transmitted is accurate and without deviation. With the MMS simulation an additional software called IED Explorer is used to read and capture data from an IEC 61850 IED. This is an additional measure for data validation and a useful tool for troubleshooting and diagnostics.

4.6.4 Conclusion of Chapter

This chapter uses data captured during the Modbus and MMS simulation to dissect the data exchange between the RTDS simulator running the PV system and the PPC. From the analysis of this data, it is possible to see the real-time behaviour of both protocols as well. This behaviour demonstrates that the client-server model of each protocol is implemented. However, the MMS protocol makes use of a more advanced request and respond mechanism versus the polling nature of Modbus. This is of particular interest if applying this simulation in broad as the real-time data exchange for MMS is more reliable as it is event driven over and above being polled as seen with Modbus. This is a important criteria for noting as these communication protocols implemented should be done on the basis to achieve the best form of operational efficiency and system reliability

This comparative analysis forms the basis of Chapter 5. Chapter 5 provides a summary of the report and is the conclusion of the research project. Future recommendations are explored, and the findings of this report are stated.

Chapter 5: Conclusion and Recommendations

The conclusion of this research project is detailed in Chapter 5. It is noted that Chapter 5 revisits the aim and objectives of this research and provides thesis deliverables. Reviewing the information uncovered in the research literature, the methodology of the lab-scale implementation, and finally, the analysis of the results provides data that is used to draw upon a conclusive statement. This conclusive statement is compared to the initial hypothesis, and based on the findings of this research project, future recommendations are suggested.

5.1 Introduction

The final chapter of this research project concludes all the research literature and results from the lab-scale implementation. This process compares the initial hypothesis to actual findings. The research aims and objectives are discussed along with the deliverables, which include all the research regarding the various components in the compilation of this study. The conclusion of this report leads to suggestions for future recommendations and possible applications for this research.

5.2 Aim and Objectives of the Thesis

This thesis investigates the potential adoption of the IEC 61850 MMS protocol for applying advanced communication between the PV inverters and PPC. Modbus is the only protocol adopted for this application, and no original equipment manufacturers have developed alternative options.

5.2.1 Aim

To improve data transmission, investigate the IEC 61850 MMS communication protocol against the long-established Modbus for power plant control systems.

5.2.2 Objectives

- The objective of developing a comprehensive understanding of Modbus and IEC 61850 MMS protocols has been achieved throughout the literature review, which involved applying that information in a simulation system.
- The literature review provides an in-depth analysis of the components in PV inverters, power plant controllers, and advanced communication protocols. These chapters provide the core functionality of the research project.
- Utility-scale PV farms must receive Grid Code Compliance certification to generate load onto the power grid. This GCC testing procedure relies on the PPC communicating setpoints to the PV inverters. The literature review has studied this advanced communication and control in depth. Furthermore, the proposed IEC 61850 MMS protocol shows various advantages over the established Modbus.
- SEL 3555 RTAC has been configured as a client in both Modbus and IEC 61850 MMS instances.
- This research project analyses the potential for implementing a new communication protocol for PV inverter communication. The IEC 61850 MMS protocol has shown multiple advantageous and advanced features that the Modbus protocol is not capable of.
- The scalability of IEC 61850 MMS is highlighted for future use due to the construction of the standard and the advanced features available.

5.3 Thesis Deliverables

The thesis deliverables are provided in subsections based on the literature review, modelling, and configuration of the simulation, as well as the comprehensive analysis.

5.3.1 Comprehensive Literature Study and Review of Main Aspects

Literature on the current state of technological developments. The details of various topologies surrounding inverters have been researched and concluded. The current state and development of PPC integrated towards monitoring and controlling PV systems has been detailed. The research then explores the functionality and adoption of both Modbus and IEC 61850 MMS protocols.

5.3.2 PPC Modelling and Configuration Compatible with RSCAD Fx Simulation

Modelling a PPC as a client for both Modbus and IEC 61850 MMS. Simulation of a PV system configured to communicate with external PPC. This communication must be adjusted from Modbus to IEC 61850 MMS while keeping the remaining components of the simulation consistent. The complex signal mapping for the IEC 61850 GTNETx2 card involved using the ICT software. The functionality that arises from the more complex data mapping provides advanced features and higher data availability

5.3.3 Comprehensive Performance Analysis of the Communication Protocols for the PPC

The comparison of the performance analysis for each protocol provides insight into the advanced features embedded in IEC 61850 that are not available with Modbus. This functionality includes timestamping, quality bits, reports, higher data availability, and advanced data types. Modbus is still effective and efficient as the recorded response to queries is marginally quicker than the IEC 61850 MMS.

5.4 Possible Application of the Research Output

This research outlines the benefits and capabilities of providing IEC 61850 MMS communication to PV inverters. This research could then assist the development of future communication modules configured in IEC 61850 compatibility. This would improve the control and monitoring of PV systems worldwide.

5.5 Recommendation for Future Research

This research investigation is limited to monitoring. Future research could extend this research project and implement control and monitoring. The control could be curated to mimic setpoints received from the grid, such as active power control, reactive power control, and power factor control. The simulation environment proves very useful in these circumstances. Future research could extend to simulating the PV systems onto actual power systems and monitor the effect of the PPC controlling DERs.

5.6 Publications

This research involved a conference paper submitted to SAUPEC 2025, and a journal article will be submitted as follows:

1 R. Johnson, S. Krishnamurthy, H. Mataifa, and M. Esmail, “A comparison study between Modbus and IEC 61850 MMS Protocols”, 2025 33rd Southern African Universities Power Engineering Conference (SAUPEC 2025), Pretoria, 29-30 JAN 2025, pp.1-6. (**Under Review)**

2 R. Johnson, S. Krishnamurthy, H. Mataifa, and M. Esmail, “Application of the Real-Time Digital Simulator (RTDS) for evaluating and comparing the Modbus and IEC 61850 MMS communication protocols in power plant controllers (PPC)”, pp 1-8. The paper will be

submitted to the Journal of Electrical Engineering & Technology (JEET), Korean Institute of Electrical Engineers, Springer Nature.

5.7 Conclusion

The investigation towards implementing IEC 61850 MMS communication between PV inverters and PPC showed positive results. The research literature exposed the current state of technology regarding PV inverters and power plant controllers. The lab-scale implementation developed a method to test the effectiveness of the IEC 61850 MMS in contrast to the established Modbus protocol. The simulations compiled provide PV systems running on RTDS NovaCor machines communicating externally to the SEL 3555 RTAC acting as the PPC. The data is captured during the simulations and this data is then analysed. Comparing the data between the Modbus simulation and the IEC 61850 MMS highlights the complexities achieved by implementing the modern IEC 61850 standard. The research question is based upon improving real-time data exchange, operational efficiency and system reliability. This is question is answered in Chapter Four as the data captured between the simulation displays characteristics of the two protocols. It is highlighted that the MMS protocol achieves advanced real-time communication as it is more sophisticated in its design to have event driven data exchanges. This is compared with Modbus's nature to poll information on a clock cycle. Furthermore, the operational efficiency is improved in the comparison between Modbus and MMS as the MMS protocol includes advanced features such as timestamping and reporting. Timestamping allows a GPS clock to time stamp accurate time tags to events. This is a crucial factor in SAS as understanding the order events is crucial for diagnostics. The report functionality that MMS includes also enhances data availability. His is done through configuring buffered reports for critical data that if the device does not receive the data the message remains in a buffer zone for a determined time. The familiarity with Modbus is likely a driving force keeping it in its position. However, with the world becoming more and more dependent on data a shift from Modbus to IEC 61850 MMS seems likely due to the added features, higher data availability and advanced data types.

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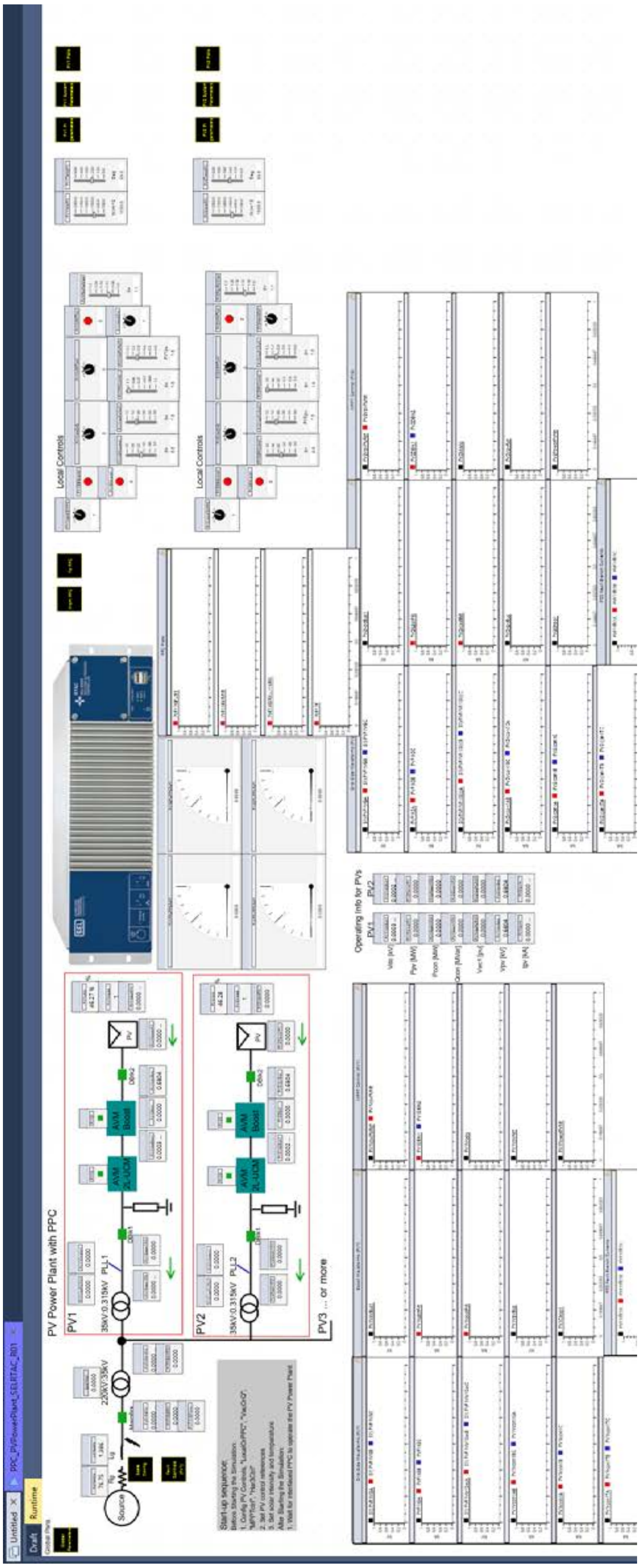
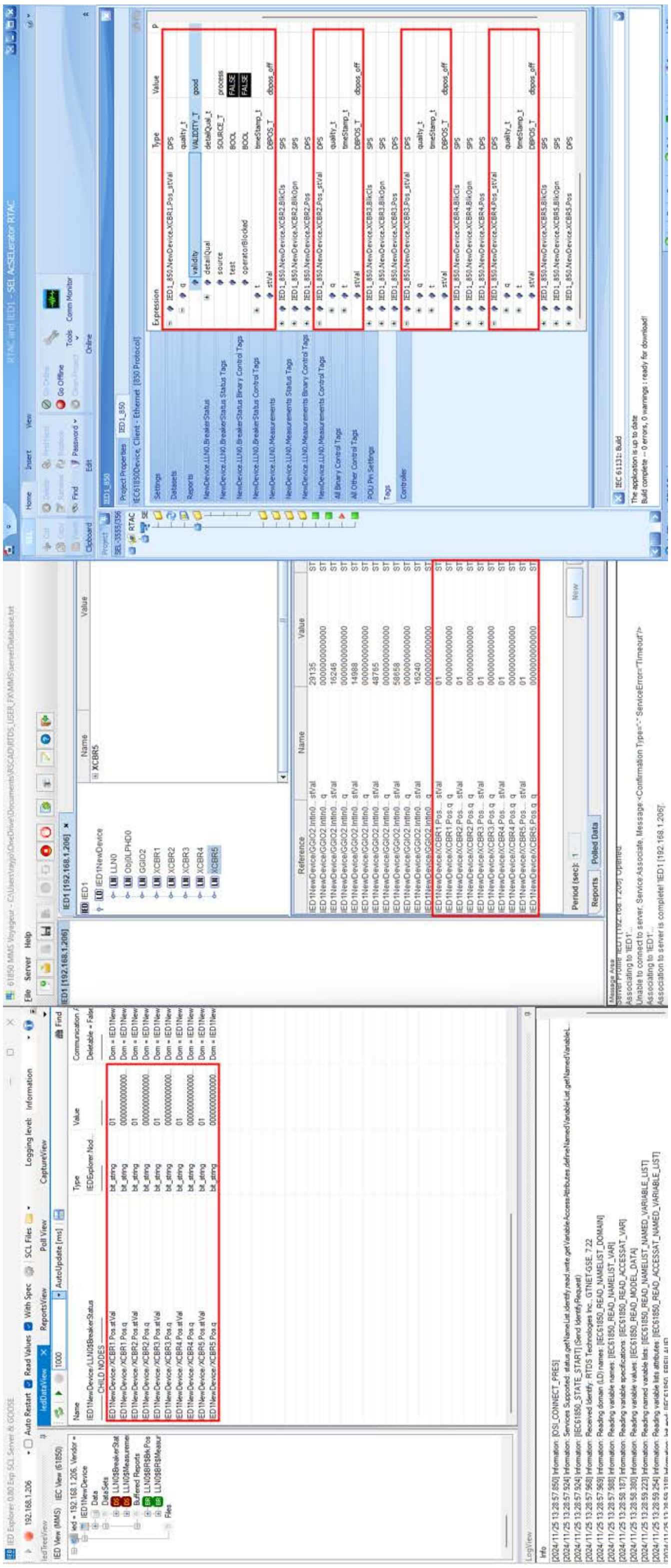
APPENDIX A: RSCAD FX Runtime Initial State

Appendix A provides a screenshot of the RSCAD Runtime of the PV system simulation in its initial state, with the breakers in the open position and represented by green indication lights.



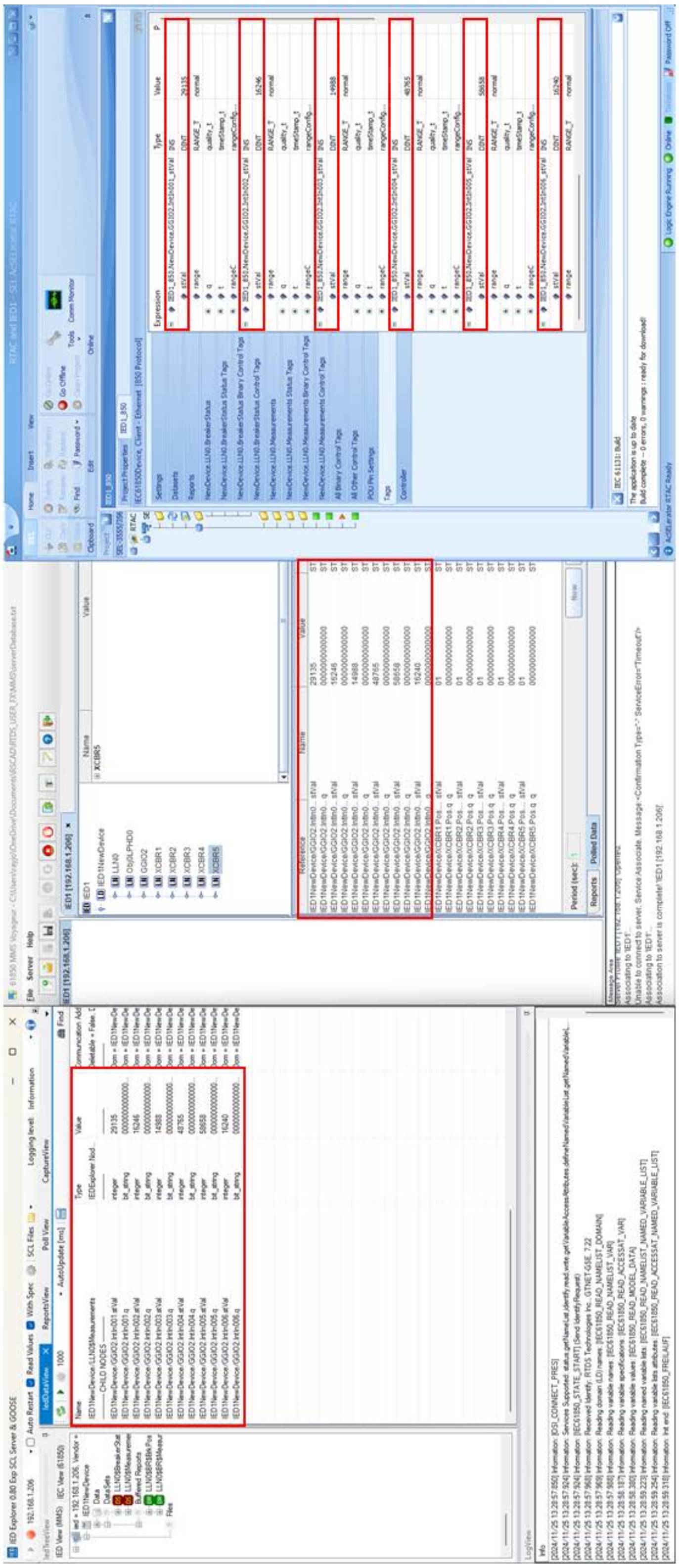
APPENDIX B: MMS Validation using IED Explorer: ‘BrkPos’

Appendix B shows the IED Explorer used to validate the data displayed in the SEL RTAC. Furthermore, the RTDS MMS Voyager shows consistency in data regarding breaker positions.



APPENDIX C: MMS Validation using IED Explorer: 'Measurement'

Appendix C shows the IED Explorer used to validate the data displayed in the SEL RTAC. Furthermore, the RTDS MMS Voyager shows consistency in data regarding measurement values.



APPENDIX D: RSCAD FX Runtime Running State

Appendix A provides a screenshot of the RSCAD Runtime of the PV system simulation in its running state. The respective measurements P, Q, V, f are noted in PPC plot window.