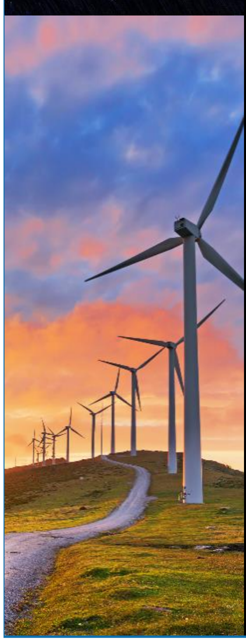

Microgrid Modeling & Simulation Applications

RTDS Technologies

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1 Microgrid Modeling and Simulation

The increasing relevance of microgrids and the distributed energy resources (DER) that comprise them has generated a demand for detailed study tools and sophisticated hardware-in-the-loop test facilities to evaluate the operation of the associated control, protection and power devices on the grid. The best method to study challenges regarding microgrid implementation is using detailed simulation programs and models. Electromagnetic transient (EMT) simulators, such as the Real Time Digital Simulator (RTDS), have been well established for detailed analysis of power system transients in the time domains from DC to kHz frequencies found in power electronic converters. The advantages of real time simulation for microgrid modeling and simulation applications include:

- **Continuous real time simulation:** Microgrid analytical studies can be performed much faster than with offline simulation programs. Since the simulator operates in continuous real time, the simulated system can operate in a manner similar to the real microgrid system. As the simulation parameters are modified and contingencies are applied, the user can watch the microgrid system respond in real time.
- **Hardware in the loop (HIL) Testing:** The HIL capability of real time simulators allows the design and operation of microgrid control, protection and power devices to be evaluated under realistic operating conditions before they are installed in the actual microgrid system.

This document discusses modeling microgrid systems on the RTDS. A Real Time Microgrid Control HIL application will also be discussed.

Please note: *The microgrid cases described in this document serve as helpful references for users interested in microgrid simulations on the RTDS. As such, no attempt has been made to optimize the controls or the operation of the microgrid for sequences other than those described. Interested readers are encouraged to modify the provided cases and/or develop their microgrid cases to meet the specific application*.

2 Microgrid Concept: Definition and Challenges

Microgrids are localized groups of electric power generation sources and loads. Microgrids can be operated in parallel with the main utility or independently as a power island. The microgrid concept is gaining rapid attention worldwide as an enabling technology to increase grid resiliency and reliability during severe weather conditions and emergency events. Additional benefits of microgrids include integration of renewables and alternative energy sources, energy access to remote and developing communities, grid support functions such as voltage regulation in low and medium voltage distribution networks. Microgrid implementations include campus environments, military operations, private installations, utility systems, large commercial and industrial loads, and remote/off-grid communities.

Microgrid operation is evidently different to traditional power systems and technical challenges related to control, communication and protection have to be addressed to ensure successful and reliable microgrid implementation.

2.1 Microgrid Control

A significant challenge to microgrid implementation is the stable control of voltage and frequency during grid-connected and islanded operation. Microgrid control structures are classified as centralized or decentralized. Fig 2-1 shows a typical structure of a centralized microgrid control. The central control unit (CCU) coordinates the microgrid control and protection functions by sending operating commands to the local control units (LCU) and circuit breakers during grid connected and islanded operation [1]. Frequency control such as load shedding is also coordinated by the CCU to maintain the power balance between loads and generation during islanded operation. The CCU may include several optimization algorithms to determine the optimum operating points of the LCUs such as cost pricing, fuel use, grid availability, faults, load forecasting, and climate models for renewables. In decentralized microgrid control structures, each component is independently controlled by its local control unit and does not co-ordinate with other local control units. Typically, due to the wide spread topology of power system networks and electrical coupling between power system components, microgrid implementations are a combination of centralized and decentralized control structures [2]. Fig 2-2 shows the hierarchy and functions of combined centralized and decentralized microgrid control classified into primary, secondary and tertiary levels [2].

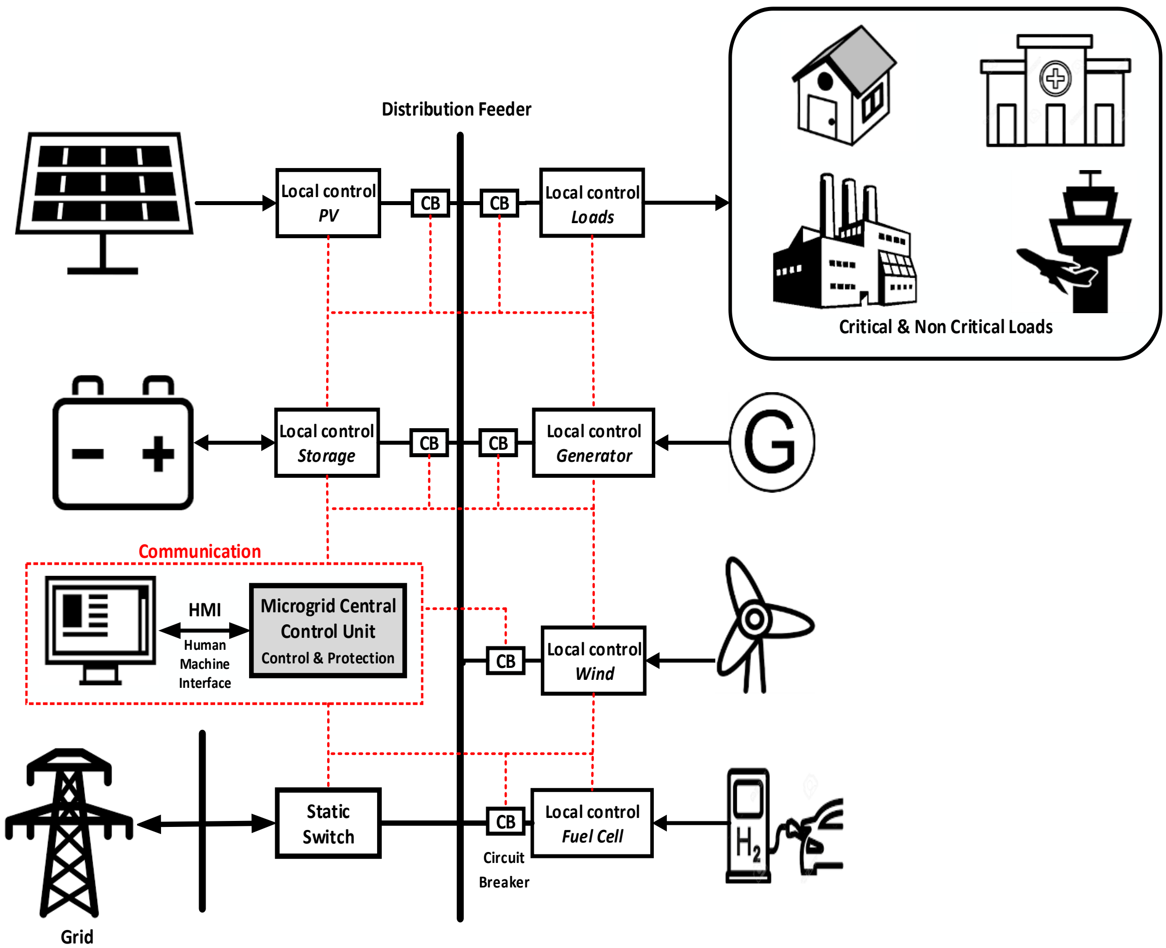

Fig 2-1: Centralized Microgrid Control Structure.

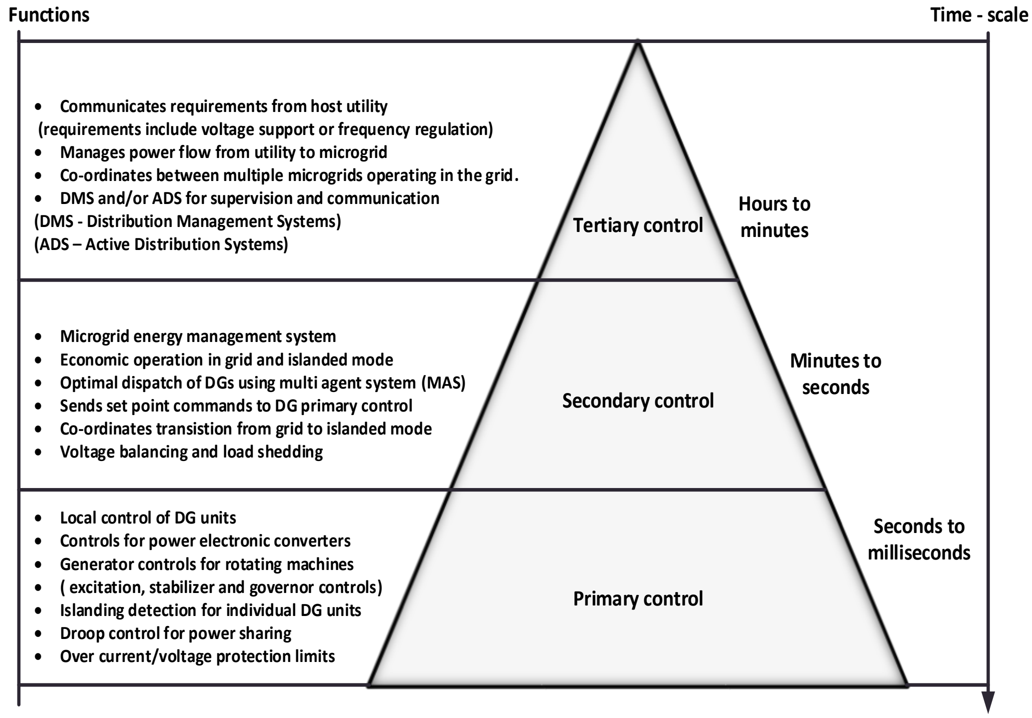

Fig 2-2: Microgrid Control Levels.

2.2 Microgrid Protection

Microgrids must be properly protected during grid connected and islanded operation. Applying conventional protection concepts based on unidirectional power flow in microgrids becomes challenging due to bidirectional power flow from multiple distributed energy resources. The transition from grid connected to islanded operation has to be properly detected to avoid instability and injury/death to power system personnel unknowingly working on lines energized by the microgrid island. Reconnecting the microgrid with the main utility should only occur when the voltage, frequency and phase of the islanded microgrid are synchronized with the grid within specified operating limits.

Key design requirements for microgrid protection schemes include ***reliability, resiliency and redundancy***. Typically, overcurrent and differential protection schemes are implemented in microgrids [3]. The need for novel microgrid protection schemes to fill the gap between overcurrent protection (low cost, low reliability) and differential protection (high cost, high reliability) schemes is discussed in [3].

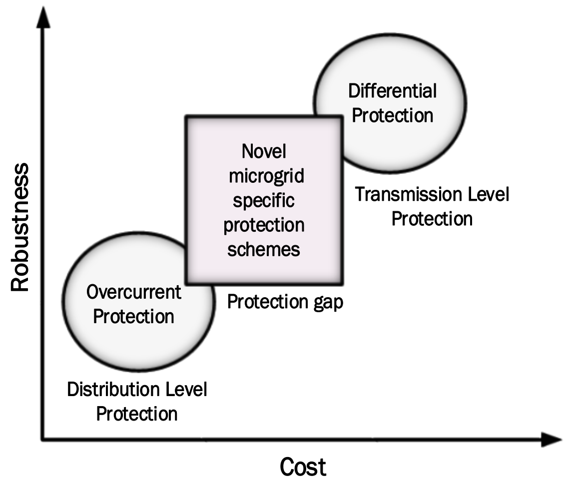

Fig 2-3: Novel protection schemes required to fill microgrid protection gap [3]

2.3 Microgrid Communication Networks and Protocols

Microgrids require dedicated and cost-effective communication networks to coordinate their control and protection functions during different operating modes. Key considerations for microgrid communication networks include:

- Data delivery within time frame of microgrid control levels and functions.
- Data access at multiple locations (wide area /long distance communication).
- Built in redundancies to handle communication breakdown and/or equipment failure.
- Interoperability between different vendor equipment and communication protocols.
- Data protection and security.
- Flexible, easy to install and maintain.

The demand for reliable and efficient microgrid communication networks has driven the development of different information and communication technology (ICT) protocol enabled devices [4]. The RTDS network interface card (GTNET) supports the following industry standard communication protocols for microgrid applications:

- Transmission Control and User Datagram Internet Protocols (TCP/UDP).
- Distributed Network Protocol (DNP3) and IEC 60870-5-104.
- IEC 61850 GOOSE and Sampled Values (SV).
- IEEE C37.118 for Phasor Measurement Units (PMUs).
- MODBUS.

2.4 Microgrid Standards and Reports

Table 2-1 lists several standards and technical reports that address technical and regulatory issues and requirements for microgrid implementation.

Table 2-1: Standards and Reports on Microgrid and Distributed Energy Resources.

Standard	Standard Description	Online Status
IEEE 1547 Series	IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems	Available
IEEE 2030 Series	IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System and End-use Applications and Loads	Available
UL 1741 series	Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources	Available
NEC 480, 690, 692, 694	National Electric Code Articles on Storage Batteries, PV Systems, Fuel Cell Systems, Wind Electric Systems.	Available
NEC 445, 700, 701,702	National Electric Code Requirements for Generators and Stand by Power Systems	Available
NEC 705	National Electric Code Article on Interconnected Electric Power Production Sources	Available
IEEE P2030.7	IEEE Standard for the Specification of Microgrid Controllers	In development
IEEE P2030.8	IEEE Standard for the Testing of Microgrid Controllers	In development
Reports	**Report Description**	
ANL/ESD-15/15	Guidelines for Implementing Advanced Distribution Management Systems: Requirements for DMS Integration with DERMS and Microgrids.	Available
SAND2014-1535	The Advanced Microgrid: Integration and Interoperability	Available

3 Microgrid Simulation Cases

As shown in Fig 2-1, microgrid components include transmission lines, transformers, loads, switches, controls, protection elements, and distributed energy sources. The RTDS software has extensive libraries with detailed power system, control, protection and power electronic component models for microgrid simulations. This section discusses the operation of microgrid simulation cases with their associated distributed energy resources.

3.1 Microgrid Case 1: Averaged Converter Models

Fig 3-1 shows a microgrid with three DERs namely a diesel generator, PV array and Battery system. **Minimum hardware requirements:** 2 PB5 cards/1 Novacor chassis with one core.

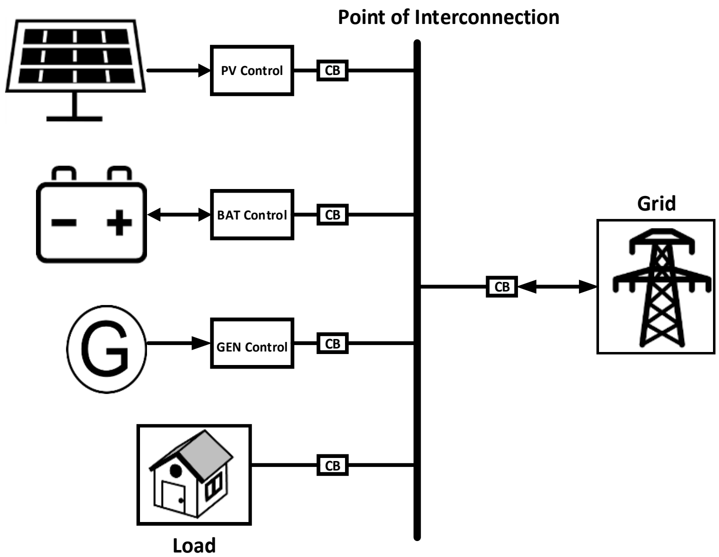

Fig 3-1: Microgrid Case 1: *Microgrid1.dft*.

The PV and battery controls are based on the decoupled ***dq*** current control strategy with internal start-up and protection logic blocks. The PV and battery sources are interfaced to the AC grid using dynamic average model of their DC/AC voltage source converter (VSC). Dynamic average models of VSCs do not represent the high switching frequency dynamics reducing the computation requirements and allows higher simulation time steps for modeling large microgrid cases.

3.1.1 Operating sequence of Microgrid Case 1

Grid Connected Operation

- Compile ***Microgrid1.dft*** and run ***Microgrid1.sib.***
- Initially, the DERs are disconnected and the load is supplied by the grid.
- Connect the DERs by turning on the switches **DIESEL**, **PV** and **BATTERY**. The load is now supplied by the DERs and the grid.
- The battery is set to discharge (PREF = +0.3 MW) and the excess power from the DERs is sent to the grid.
- Observe the battery state of charge (SOC) and set PREF = -0.3 MW when SOC < 50%.

Islanded Operation

- Disconnect the grid by setting the GRID switch = 0.
- Reduce the PV insolation to 500 W/m^2 and observe the diesel generator power increase to provide the power balance
- Set the battery to discharge (PREF = +0.3 MW) and observe the diesel generator power decrease to provide the power balance.
- Apply the fault pushbutton **FAULT** and observe how long it takes the diesel generator to control the frequency for different fault cycles. For this operating sequence, the diesel generator is operated in isochronous mode and provides the voltage and frequency control in the islanded microgrid.

3.2 Microgrid Case 2: Switched Converter Models

Fig 3-2 shows a microgrid with three DERs namely a diesel generator, PV and a Doubly Fed Induction Generator (DFIG) wind energy system [5]. The PV and DFIG sources are interfaced to the AC grid using switched VSC models with sinusoidal pulse width modulation controls.

The VSCs are modeled using small time step bridge boxes simulated at 2.5µsecs.

Minimum hardware requirements: 4 PB5 cards /1 Novacor chassis with 3 cores.

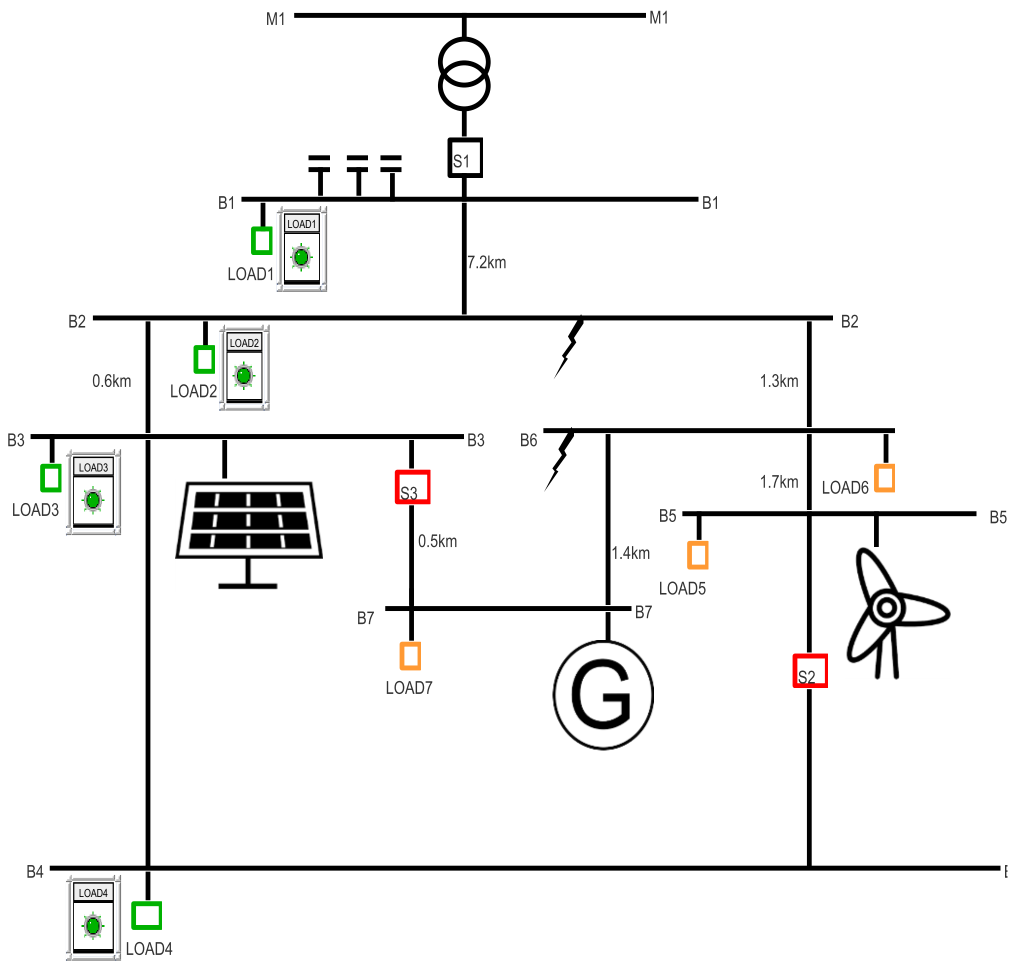

Fig 3-2: Microgrid Case 2: ***Microgrid2A.dft***

A switched capacitor bank is used to balance and control the voltages the point of connection (BUS1). This is specifically needed to enable resynchronization of the microgrid to the grid. For resynchronization, the voltage, phase angle and frequency at BUS1 should be within the limits specified in Table 3-1 [5]. A load shedding logic is implemented for Loads 1- 4 to achieve power balance and restore the microgrid frequency. The load shedding criteria is shown in

Table **3-2**. The RTDS breaker control model is used to check the synchronization criteria to reconnect the microgrid to the main utility.

Table 3-1: Synchronization Criteria

Total DER (kVA)	**Frequency (Δf, Hz)**	**Voltage (ΔV, %)**	**Phase angle ($\Delta\varphi$, ^{0})**
1500 - 10000	0.1	3	10

Table 3-2: Low Frequency Load Shedding Criteria

Stage	Criteria	Time (secs)	Load
1	$f \leq 59.5Hz$ or $\frac{df}{dt} > 1.5\,\frac{Hz}{s}$	0.1	LD1
2	$f \leq 58.7Hz$ or $\frac{df}{dt} > 1.5\,\frac{Hz}{s}$	0.08	LD2
3	$f \leq 58.3Hz$	0.08	LD3
4	$f \leq 58.0Hz$	0.08	LD4

3.2.1 Operating sequence of Microgrid Case 2

Load shedding operation

- Compile ***Microgrid2A.dft*** and run ***Microgrid2A.sib.***
- When the system reaches steady state, disconnect the grid using the **TRIP** push button.
- In islanding mode, apply a fault using the **FLT** push button and observe the load shedding operation is activated to restore the frequency in the islanded microgrid.
- After the frequency is restored in the microgrid, reconnect the shed loads by using the corresponding **RCTL** push button in the **LOAD SHEDDING** group.

Synchronization operation

- Reconnect the grid using the **RECLSC** push button. Observe the microgrid remains islanded.
- In the SYNC CTL group, observe that the voltage difference is not met based on Table 3-1.
- Switch on the capacitor banks using the **CAPS** switches in the **SYNC CTL** group until the voltage difference is less than or equal to the criteria specified in Table 3-1.
- With the synchronization criteria met, observe the reconnection occurs when the microgrid voltage phasor aligns with the grid phasor with the **RECLSC** command issued.

Note: The case ***Microgrid 2B.dft*** uses dynamic average models for the PV and DFIG Wind sources to reduce the hardware requirements. **Minimum hardware requirements** for ***Microgrid2B.dft***: 3 PB5 Cards/1 Novacor chassis with 2 cores.

4 Microgrid Control Hardware in the Loop Application

Real-time automation controllers (RTAC) are used to co-ordinate the safe and reliable operation of the microgrid in grid connected and islanding operation. In this section, a control hardware in the loop application is demonstrated using the SEL 3530 RTAC. The SEL 3530 RTAC provides "complete and flexible system control with integrated security, seamless configuration, unified logic, and reliability" [6]. The SEL 3530 RTAC converts data between multiple protocols, communicates with any configured and connected device, and comes with an embedded IEC 61131 logic engine. The microgrid simulation case and SEL 3530 microgrid program demonstrated in this application are developed by SEL Engineers Bharath Nayak and Will Allen.

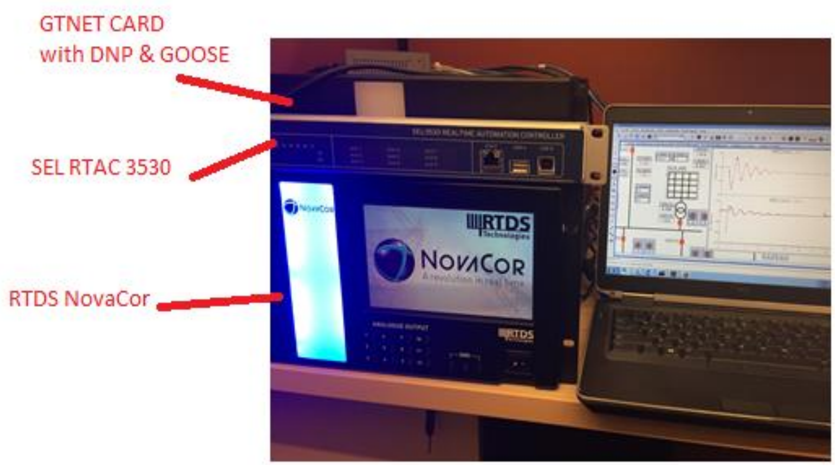

Fig 4-1: Microgrid CHIL Interface

4.1 Banshee Microgrid CHIL Simulation Model

The Banshee Microgrid simulation model is shown in Fig 4-2. The system consists of three radial feeders supplying a real-life industrial park [7]. The generation assets consist of a 4000 kVA diesel generator and a 3500 kVA natural gas-fired combined heat-and-power (CHP) system. The system also includes a simulated 5000 kW PV and a 2000 kVA battery energy storage (BES) [7]. More details on this microgrid system is provided by the MIT Lincoln Laboratory repository https://github.com/PowerSystemsHIL.

Minimum hardware requirements: 6 PB5 cards/1 Novacor chassis with 3 cores.

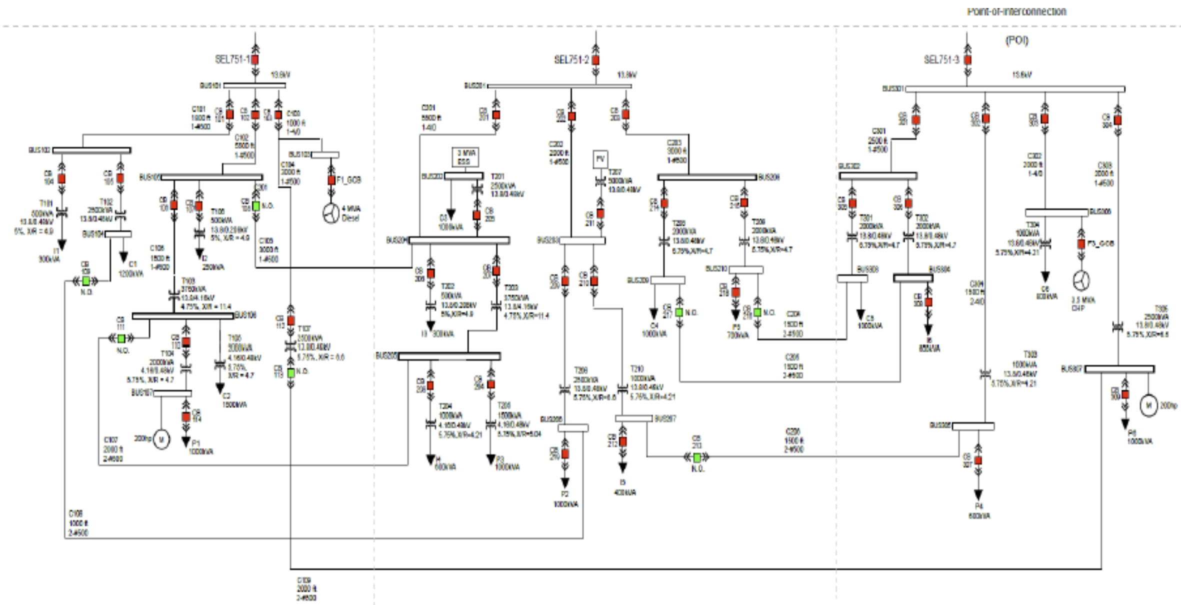

Fig 4-2: Banshee Microgrid Simulation Model

The signals sent from the microgrid simulation model to the SEL 3530 RTAC include real and reactive power measurements, breaker and load control status, frequency and the DER power setpoints. The SEL 3530 RTAC is interfaced to the RTDS simulation through the GTNET card with the DNP and GOOSE protocols used for the data exchange.

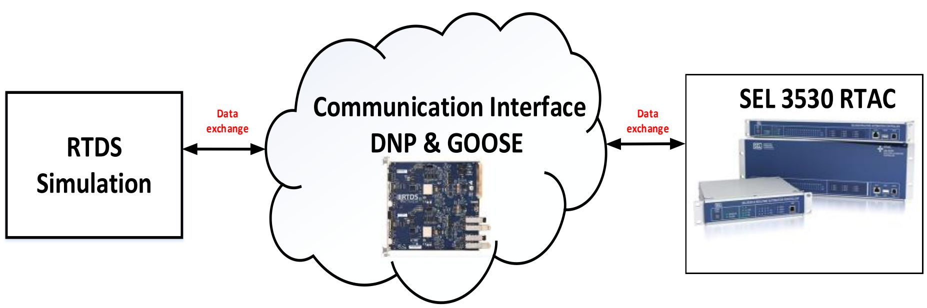

Fig 4-3: Communication Interface with SEL RTAC

Fig 4-4 shows the DNP device settings in the SEL RTAC. The Server IP address is the IP address of the ***GTNET DNP*** module. The signals sent from the RTDS simulation to the RTAC using the DNP protocol are mapped in the file ***IP_Dnp.txt.***

Setting	Value
Communications	
Transport Protocol	TCP
Client IP Port	20000
Client UDP Broadcast Port	20000
Server IP Address	172.24.9.145
Server IP Port	20000
Date-Time	
UTC Offset	0
DST Enabled	False
DNP	
Client DNP Address	0
Server DNP Address	1
Integrity Poll Period	60000
Class 1,2,3 Polling Period	5000
Poll Timeout	7000
Number of Poll Retries	1

Fig 4-4: DNP Device Settings

The IP address of the RTAC is entered in the GTNET DNP component settings. Note the DNP TCP/UDP Port Number is the same number in the DNP settings shown in Fig 4-4.

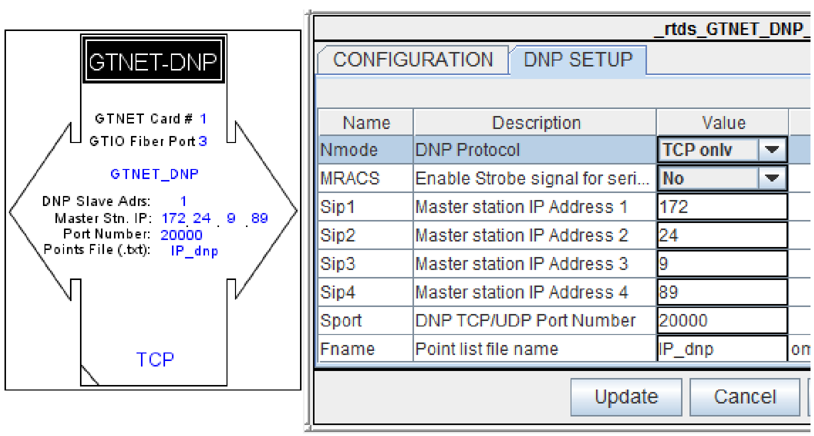

Fig 4-5: GTNET DNP component settings

The load shedding functionality of the microgrid controller is demonstrated by reducing the reference power set point of the diesel generator to 1.5 MW so that when feeder 1 is isolated from the main utility, the total load demand exceeds the available generation, with the breakers connecting feeder 2 and feeder 3 opened. The load shedding signals are sent using the GTNET – GSE component with the map signals in the corresponding SCD file. After the islanding event, the power flow and frequency changes is detected in the SEL RTAC which initiates the load shedding logic of the microgrid control program to restore the feeder frequency.

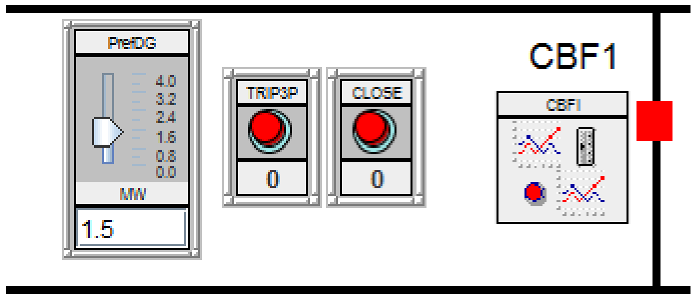

Fig 4-6: Diesel generator Pref setpoint and breaker to island Feeder 1

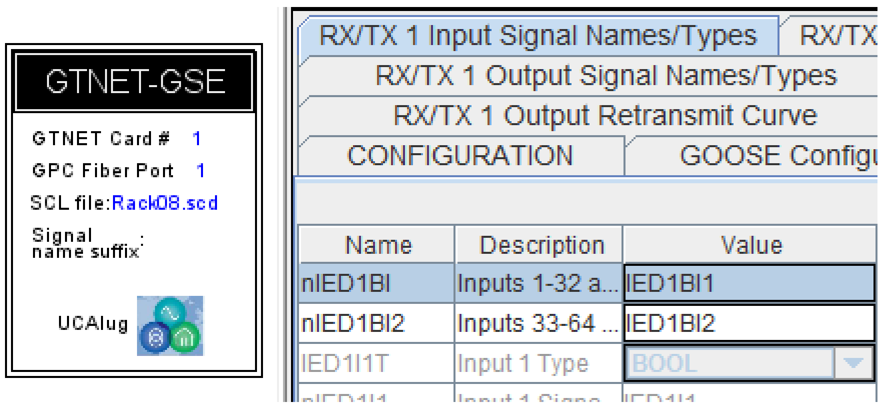

Fig 4-7: Input signals from SEL RTAC using GOOSE

5 References

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