ABSTRACT

DONG, XINYANG. Implementation and Evaluation of Control Protocols for Microgrid Testbed. (Under the direction of Dr. David Lubkeman).

Microgrids are being discussed and developed both in concept definition and implementation in real world applications, having demonstrated its effectiveness and efficiency to the world in a number of cases. As one promising architecture to realize a more active and efficient distribution grid, a microgrid is capable of dealing with the increased complexity of maintaining power quality, as well as making economic market decisions where more distributed energy resources are added at the distribution grid level.

In the Olney Town Microgrid Project, a microgrid control system is developed and tested to increase resiliency, reduce emissions, and improve efficiency in accordance with Department of Energy (DOE) goals. The FREEDM System Center is in charge of developing a microgrid testbed and testing microgrid controller functionalities in the project.

As part of the Olney Town Microgrid Project, the study in this thesis includes validating individual microgrid components models and power flow as a whole entity. A communication interface utilizing DNP3 protocol is implemented and tested within the model, in order to provide sufficient communication capability between the microgrid controller and the testbed. Several test plans are designed to perform tests referred to in microgrid controller design documents and microgrid use cases. A prototype DNP3 master station is also developed in LabVIEW, to give more flexibility in future testing. Finally, a summary of the study in the thesis is discussed and a vision for possible future research is given.

Implementation and Evaluation of Control Protocols for Microgrid Testbed

by
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DEDICATION

To my parents and close friends who supports me through my master program.

To my teachers and classmates who generously share their knowledge with me.

BIOGRAPHY

Xinyang Dong comes from Zibo, China. She received her Bachelor's degree in Electrical Engineering and Automation from Beijing Jiaotong University, Beijing, China in 2013. She started her Master of Science degree studies at North Carolina State University in August, 2013. Her research interests include Power System Protection, Automation and Control, Power System Communication and SCADA, Power Distribution Planning and Analysis.

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1.1 Background

In recent years, distribution grids are becoming more active in the sense that control and decision-making capabilities are being added at the local level. As more distributed resources are added, the complexity of maintaining power quality as well as making economic market decisions at the distribution grid level is dramatically increased. A microgrid, as one promising structure to realize a more active and efficient distribution grid, is being discussed and developed both in concept definition and implementation in real world applications.

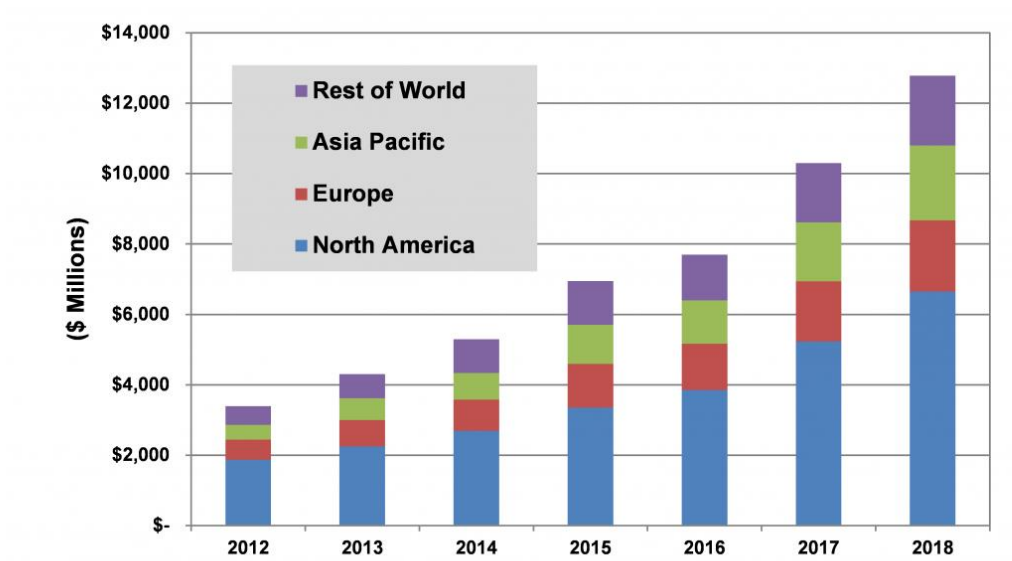


Figure 1. 1 Projected worldwide microgrid market [19]

1.1.1 Microgrid

And what is microgrid? A definition from Microgrid Exchange Group (MEG) is "A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode."

In structure, a microgrid often contains multiple distributed energy resources (DER) and several loads. These distributed resources may include photovoltaic arrays (PV), energy capacitors or batteries, and combined heat and power (CHP) generations. Loads may be controllable in some cases. Another important component is the electrical connection point of the microgrid to the whole grid, which is often called the microgrid point of common coupling (PCC).

Control capability over these DER components is also one key feature of a microgrid [1]. The control allows the system to continue to operate and supply power to consumers when it's disconnected from the whole electric grid. A microgrid can serve a variety of customers like residential and commercial buildings, and sometimes industrial parks. [7]

A microgrid normally operates in a grid-connected mode through a distribution network infrastructure. Yet it is also expected to have the ability to provide sufficient generation capacity and controls to supply at least all critical loads when it's disconnected from the distribution system (at the PCC), remaining to operate as an autonomous entity (islanded mode). Also, the high amount of penetration introduced by DER units - like PV or wind turbines - will potentially necessitate provisions for both islanded and grid-connected operation modes, as well as a smooth transition between the two modes to best utilize microgrid resources. [7]

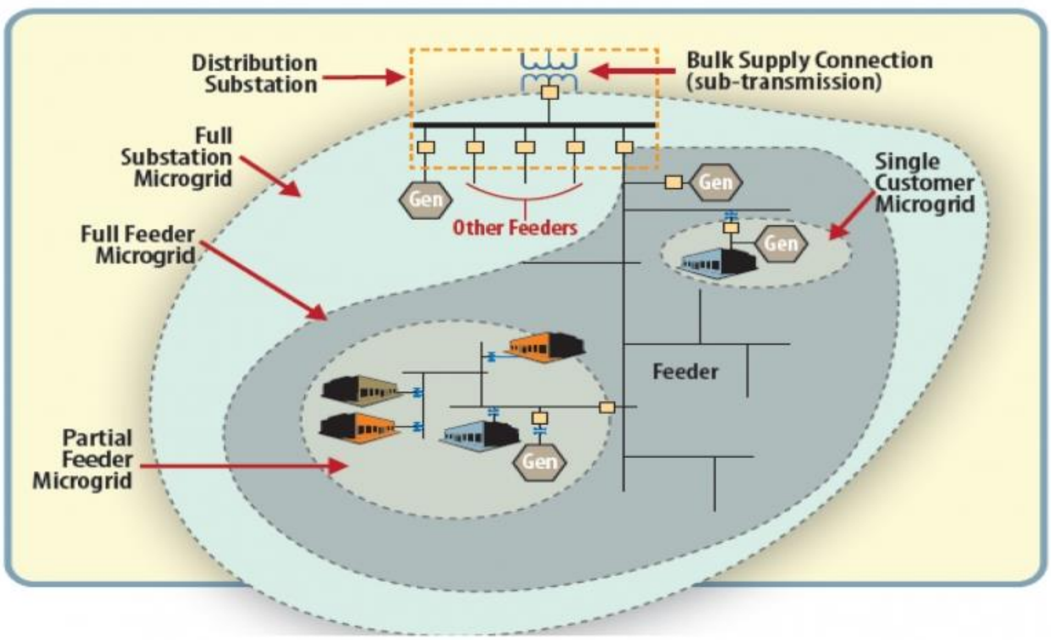


Figure 1. 2 A microgrid example [4]

The microgrid in a network provides benefits to the market, operators and consumers. The self-control feature mentioned above can also be regarded as a single load or generator at a given moment [1], reducing vulnerability and increasing resilience for the whole electric grid. Also, it can be rewarding for customers. Microgrids with distributed resources can fulfill electricity and thermal needs at the same time, reducing emissions, and may lower cost depending on the situations.

1.1.2 Microgrid Controller

Benefits brought by microgrids necessitate more complex controls. Integration of renewable resources introduces higher intermittency for systems than traditional sources. Also bi-directional power flow can also cause problems for conventional protection schemes [2].

So the environmental and economic benefits are primarily contingent on the control capabilities and operational features of the microgrid controller. A special designed control system need to be implemented into microgrids.

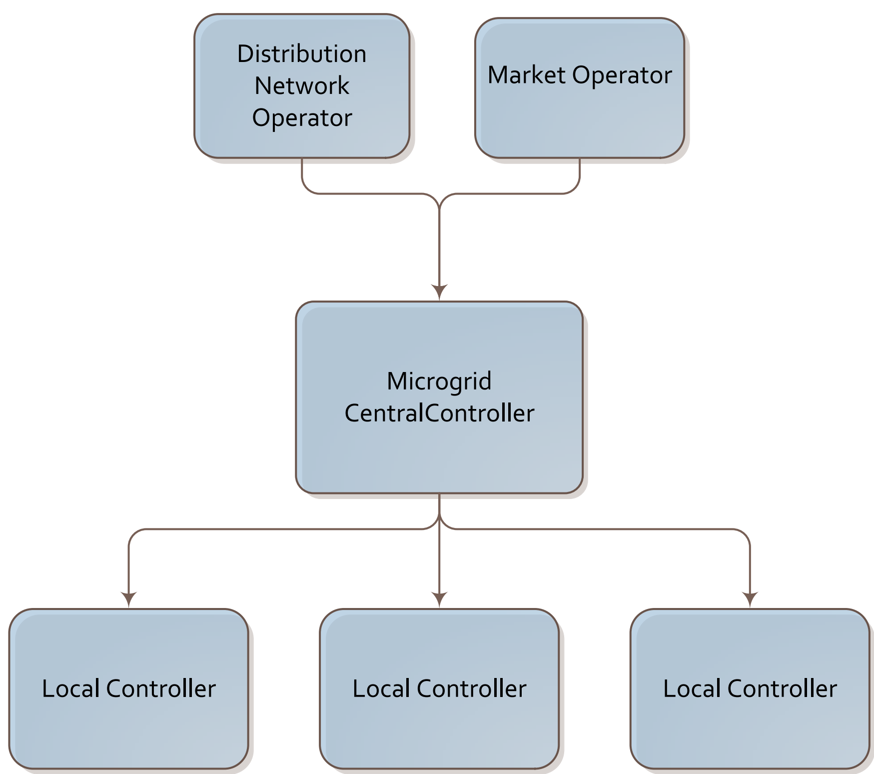


Figure 1. 3 Hierarchical control architecture

There are two-levels to microgrid control: a microgrid central controller (often referred to as microgrid controller), and local controllers. The microgrid controller is required to run long-term and real-time optimal dispatch, thereby providing optimal set-points for the supply of electrical and thermal energy. The control should also supervise the microgrid to maintain voltage and frequency stability, ensuring power quality. The controller also needs to be making the right decisions when a failure occurs, or manage black start subsequent to a failure. The microgrid controller needs also to ensure the participation in the energy market, and provisioning the microgrid for ancillary service.

Each microgrid asset or a combination of them contains one local controller to apply commands from the central controller and control their own parameters at desired level. Depending on the control approach, each local controller may have a certain level of intelligence. In a centralized control strategy, each local controller receives commands from the corresponding microgrid controller (central controller) for some of the operating parameters. In a decentralized control strategy, each local controller makes decisions locally on more parameters, leaving less space for the central controller to participate. Also some decisions can only be made locally in either approach, like a local controller does not need a command for voltage control. [7]

As is shown in figure 1.3, there are other important roles referred in microgrid control system, like distribution network operator and market operator. In a system, a distribution network operator is intended for dealing with area where multiple microgrids exist; and microgrid operator is responsible for the market functions of each specific area. The two entities normally are not counted as parts of the microgrid; they are more like delegates of the whole electric grid which effect microgrid through decisions made by microgrid controller. So in this thesis we would not lay much importance on them.

1.1.3 Microgrid Modeling

In the process of microgrid controller developing and commissioning, it’s not very possible to connect the controller with a real microgrid and operate. In order to test the functionalities of a microgrid controller, a microgrid testbed is needed. Planning and operating microgrid decisions directly depend on modeling of the microgrid, and test results of microgrid controller operating on the microgrid model. To make sure the microgrid controller is capable of making reasonable technical and commercial decisions, the models should reflect the real world accurately and clearly.

Obviously, neither a too conservative nor a too aggressive model is satisfying, which can lead to inaccuracy of the tested controller within our perspective.[3] Thus a pragmatic model is crucial in deciding whether the microgrid controller is advanced or mediocre. When simulating a specific microgrid, we need to know components and their features, electric and communication connection between components and controller, and expected operating principles. Validations of the microgrid model will be executed in different situations to make sure the model response reflect correct features of practical microgrid.

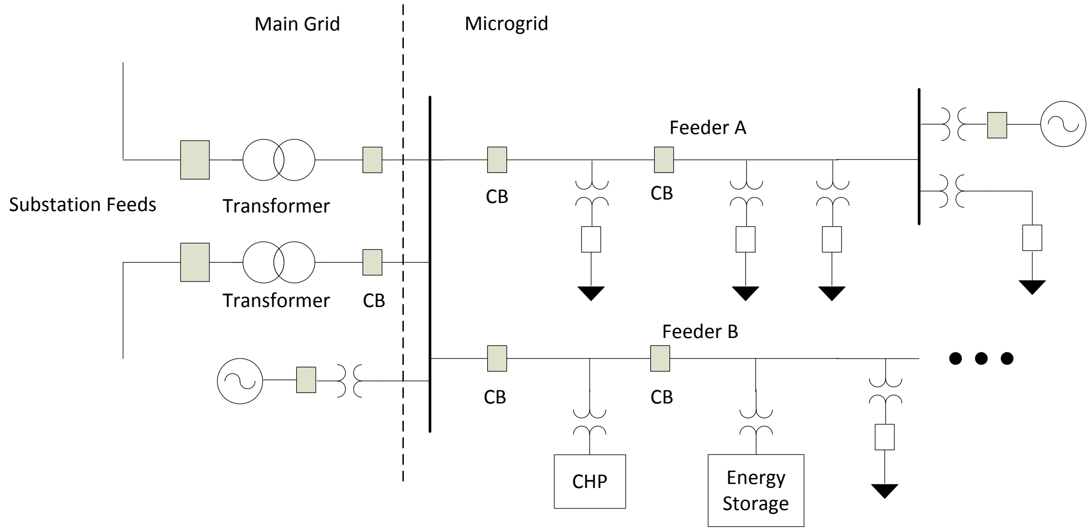


Figure 1. 4 An example microgrid one-line diagram [20]

1.2 Microgrid Examples

Microgrid projects have been undergoing a fast increase for the last few years. The following contents will present several microgrid examples of projects, accomplished or still under construction, which provided their value in critical situations.

1.2.1 New York University

As one of the largest universities in the United States, New York University has been producing power on site since the 1960s and installed a large oil-fired cogeneration plant in 1980. At the end of that facility's service life, NYU made a decision to transit from oil-fired technology towards a modern natural-gas fired, combined heat and power facility (CHP), with eyes towards microgrid capabilities with better resilience and better control over energy expenditures.

The CHP system has an output capacity of 13.4 MW (twice as much as the old plant's capacity) and has been fully operational since 2011, supplying power to 22 buildings and heat to 37 buildings. The microgrid consists of two 5.5 MW gas turbines for producing electricity coupled with heat recovery steam generators and a 2.4 MW steam turbine. The NYU microgrid is connected to wider area distribution grid and purchases electricity when demand cannot be met on site.

Based on microgrid upgrades, the NYU microgrid is now able to operate in island-mode and disconnect from grid. It has been successfully tested during Hurricane Sandy, when the NYU microgrid successfully islanded from the local distribution grid and continued to reliably power much of the NYU campus.

The transition towards microgrid implementation of the plant has proven its benefits both economically and environmentally. Savings on total energy costs is $5 to $8 million per year, evaluated by NYU. It also reduced NYU's local emissions drastically, with an estimated 68% decrease in EPA criteria pollutants (NO_x, SO_2, and CO emissions) and 23% decrease in greenhouse gas emissions. This is a great step towards the commitment the university made to the City of New York—to decrease its greenhouse gas emissions by 30%.

1.2.2 Borrego Spring Microgrid

The Borrego Spring microgrid project is based on an existing utility circuit, built in an area of San Diego Gas and Electric Company's (SDG&E) service territory, covering 2,800 residential customers. This project mainly focused on designing and implementing an innovative microgrid that integrates the distributed resources and resources on the customer-side. [10] The goal of the project is to provide a proof-of-concept test as how microgrid—or information technologies and distributed energy resources combined together can increase utility asset utilization and reliability.

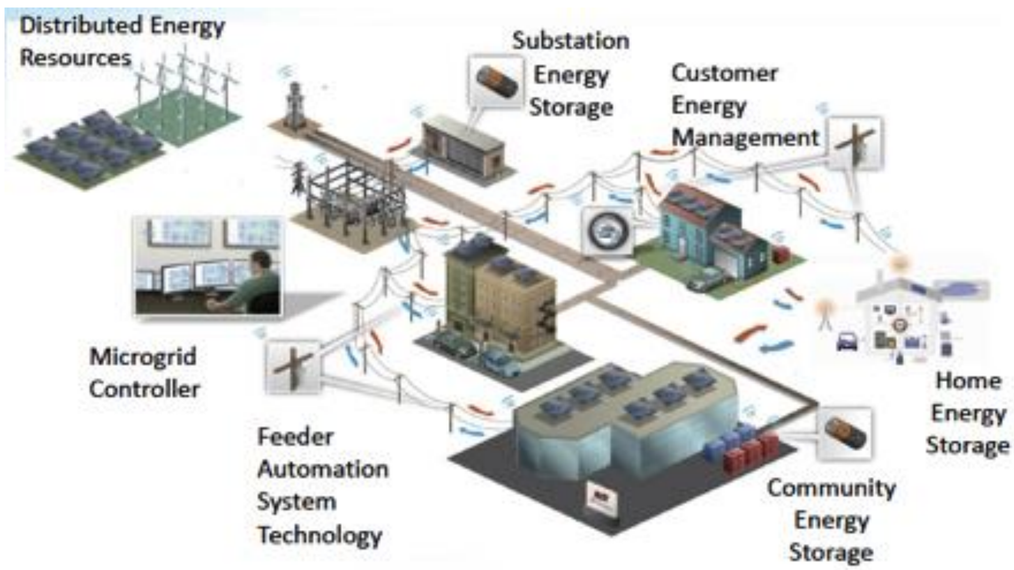


Figure 1. 5 Borrego Spring Microgrid Architecture [21]

In order to achieve goals listed above, the microgrid design looked at optimizing assets, managing costs, and increasing reliability. Technologies that were integrated into the microgrid included automated demand response, renewable resources, and other advanced technologies. [10] This project also included a focus on assessing the impact and viability of microgrids on aspects of energy costs and price volatility.

The total capacity of the microgrid will be about 4 MW, including two 1.8 MW diesel generators, a large 500 kW/1500 kWh battery at the substation, three smaller 50 kWh batteries, six 4 kW/8 kWh home energy storage units, about 700 kW of rooftop solar PV, and 125 residential home area network systems. [11] The community is an isolated area fed only by a single sub-transmission line. Now islanding of the entire microgrid is being demonstrated for reliability verification. By using the smart meters and home area network devices, SDG&E is also exploring the price driven demand response possibilities, via interacting with storage devices, electric vehicles, and smart appliances. Supervisory control and data acquisition (SCADA) is incorporated on all circuit breakers and capacitor banks, Feeder Automation System Technologies (FAST), outage management systems, and price driven load management at the customer level.

1.2.3 Sendai Microgrid

The Sendai Microgrid Project, one of the most well-known microgrid demonstrations, was one of the four major New Energy and Industrial Technology Development Organization (NEDO) projects carried out in Japan. It is located on the campus of Tohoku Fukushi University in Sendai City in the Tohoku district, and initially was designed in 2004 as a test bed for a demonstration project of the NEDO. The study was completed in 2008, and after that the microgrid system continued to operate as a highly successful project.

On March 11, 2011, the devastating Great East Japan Earthquake hit the Tohoku district, resulting in catastrophic damage on the district and its energy supply system. Despite the extreme devastation, the Sendai Microgrid continued to supply power and heat to customers, proving its effectiveness and excellent performance, thus becoming a microgrid superstardom known world widely. [12] After a few hours of service loss, generators on site were started and the microgrid supplied the teaching hospital of Tohuku Fukushi University with both power and heat during the two-day blackout.

The energy center contains two 350 kW natural gas generators, 50 kW of PV, and modest battery storage. Power quality of six varying levels is another notable feature of this project. The control room, which is supplied by one of the six levels, is designed to be in a direct DC circuit. All devices are designed to be in DC to avoid disturbance propagation, including data racks. [13]

Figure 1. 6 Sendai Microgrid

1.3 Project Background

The work described in this thesis is part of the Department of Energy Olney Town Center Microgrid project. This project will design and develop a microgrid controller, namely Green Energy Bus, to provide Montgomery County, Md. with developed and lab-tested control system technology options, to increase the resiliency of the Olney Town Center area.

The Montgomery County Planning Board in 2005 established the Olney Town Center as "a civic center/town commons", not only because it serves as a key point of interaction in the community, but also because it contains numerous vital community assets. With an estimated total peak electrical load of 7 MW, the Olney Town Center is an area directly serving a suburban population of more than 33,000 residents. It contains a hospital, a police station, two fire stations, two schools, grocery stores and gas stations, the community's water tower, and some other assets. Moreover, the Olney Town Center is located at the crossing of two state highways that represent major regional arteries for commerce and public safety in Montgomery County.

Figure 1. 7 Olney Town nodes map

These features make the Olney Town Center an ideal candidate when considering microgrid deployment. If this center of essential services is operating properly with microgrid deployed, the Olney community could function normally for weeks even during a regional outage. To allow the community to achieve greater resilience, obviously a more powerful, extensible, and cost-effective microgrid control system is needed.

To achieve the community's objectives, the Olney Town Microgrid team will design a microgrid control system capable of integrating distributed renewable energy resources, natural gas CHP units, energy storage, and demand-side management technologies in near-real-time optimization schemes. In this project, particular to the needs of this community, resiliency, efficiency and economics are interrelated. If the system design achieves its goal, the system will reduce the Town Center’s carbon footprint by 20%, and improve its energy efficiency by at least 20%.

The role of FREEDM Center in this project is to lead and execute all microgrid control systems testing for the project, and supports engineering analysis and test results reporting. In other words, FREEDM Center is in charge of designing and developing a microgrid simulation model to test the effectiveness of the microgrid controller developed by Green Energy Corp. And my task in this project is mainly to build DNP3 communication interface in model, and launch model validation tests as well as communication tests.

1.4 Content of Thesis

In this thesis, how a microgrid model is designed and built, how to validate effectiveness the model, and how the communication interfaces between model and a test-oriented “controller” are established is discussed.

The microgrid model is designed and developed for testing the microgrid controller, so a focus on testing specific microgrid controller features would be stressed when conducting model validation tests. In chapter 2, Olney microgrid components and methodology of modeling them are separately discussed, and a whole picture of the model platform is described. Chapter 3 is mainly focus on DNP3 interface in microgrid model, as well as a master station developed in LabVIEW which provides another choice of conducting energy dispatch tests. Chapter 4 talks about simulation validation methodology, features and functionalities of the controller, and test plans aiming to examine different features of microgrid model are given. And then model validation tests and results are shown in chapter 5, communication tests and DNP3 features are explored in chapter 6. Finally, chapter 7 is the conclusion which gives a general idea about what is achieved in this thesis, and what should be thought and conducted in the future in this project.

Chapter II. Olney Microgrid Components

2.1 Olney Town Microgrid Project Overview

As mentioned in the first chapter, the Olney Town Center Microgrid project will be focusing on researching, developing, and testing microgrid control systems FOR Olney Town Center. To provide an enhanced understanding of factors affecting community microgrid control system design requires a simulation for Olney microgrid and its operating conditions in various scenarios.

Thus a well-designed model of the Olney Town distribution grid is a primary need. Information of the grid assets and their capacities, connection of these components, and different scenarios for PV and grid connection is of vital importance when building and emulating the microgrid. Also, the control goal of the controller’s economic and environmental objectives should be clarified before design and development of the simulation. To introduce the expected functions, goals targeted should be made clear. The objectives of the microgrid controller are simply the Department of Energy (DOE) goals: a) Reducing outage time of critical loads by more than 98%; b) Reducing emissions by 20%; and c) Improving system efficiencies by more than 20%.

The goals can be achieved if certain requirements are met. Though critical loads are defined by the customer, the outage time can be measured and reported as

System Average Interruption Duration Index (SAIDI). Satisfactory accomplishment of reducing emission would be demonstrated by testing that indicating 20% reduction in emissions be achieved attributable to operation of the proposed microgrid. And a test demonstrating that the total utility-supplied electrical and thermal is at least 20% less after deployment of the proposed microgrid than that before, can be a sufficient principle which proves the efficiency goal met.

Functions for the microgrid controller including: disconnection; resynchronization and reconnection to the grid; steady-state frequency and voltage control; energy dispatch; black start; and ancillary services. The Olney Town project provides multiple user cases for various functionalities, indicating brief action sequences about how the controller and components would react in specific environments. In this thesis these use cases with controller behavior focus are used to develop testing plans for model validation. Though it's not practical to build all models and test them in all scenarios, most of the test plans are listed and several of them are conducted and results are shown. What will be considered first is whether the model can support the static energy dispatch function of the microgrid controller.

2.2 Microgrid Components

The microgrid is considered as a mix of commercial and residential community, which consists of different components that need to be taken care of separately. For an ideal microgrid, DERs will be implemented from both efficiency and environmental-friendly consideration. In this microgrid model system, PV, Combined Heat Power, energy storage system, absorption chiller and loads will be included. The community is connected to utility through utility Point of Common Coupling (PCC). The total electric load will be around 7 MW.

In order to initiate a basic testbed, FREED Center developed a generic microgrid model referred to as “Zone 0” for component modeling. The grid components for the Zone 0 model are shown below in figure 2.1:

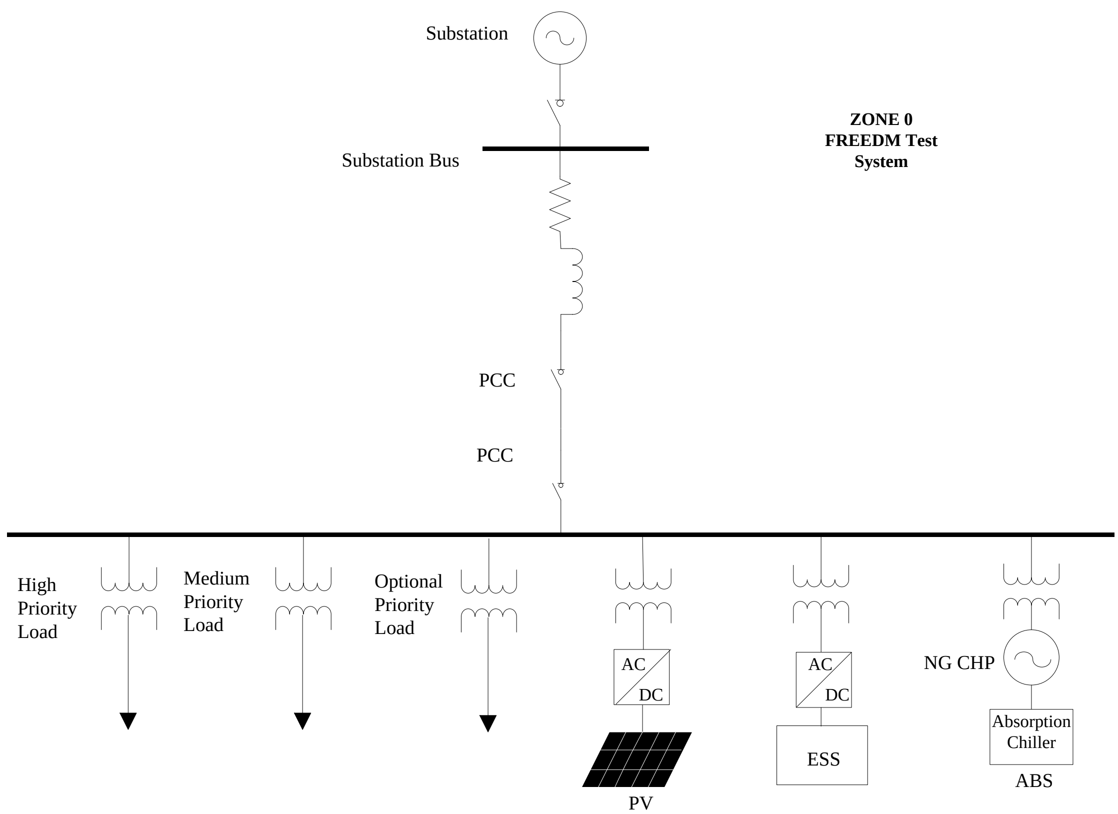


Figure 2. 1 FREEDM test system Zone 0

This system contains each of the different components of Olney Town microgrid. Loads are actually integrated together as one load using all different levels of loads. The absorption chiller is connected to the Combined Heat and Power (CHP) unit. At this time CHP unit model focuses on its static performance, and by now doesn't include any dynamic modeling.

2.3 Olney Town Microgrid Modeling

The first thing should be considered when developing the real-time microgrid model is the simulation platform.

Real-time simulation is used in many engineering fields and applications. These applications benefit from the use of real-time simulators in the following ways. First, it enables testing of simulated devices at or beyond their normal operating limits, without risking damage with real devices, especially when high power levels are involved. Second, the simulation acceleration factor obtained by the use of compiled code enables the realization of rapid batch simulations [8].

One main application of real-time simulation is Hardware-in-the-Loop testing (HIL). HIL simulation is a technique in which hardware can be connected to software models to form a single closed-loop simulation. A real time simulator (RTS) is needed to run the software model and the communication interface between software and hardware in actual time. Outputs from the hardware system can be measured and converted to digital values; these digital values are used as inputs to a software model. Then model outputs are calculated and converted to analog outputs, which are in turn sent to the hardware system to accomplish a typical HIL test circle [9].

To benefit from a Hardware-in-the-Loop testing on a real-time simulator, in this project RT-LAB from OPAL-RT Technologies Inc. is chosen as simulation platform. It is real-time simulation software which is fully integrated with Matlab/Simulink. The plan of simulation is to develop and run separate components models in Simulink first, then integrate them and run in RT-LAB with designed scenarios.

2.3.1 Combined Heat and Power

Cogeneration or Combined Heat and Power (CHP) is the use of a heat engine or power station to simultaneously generate electricity and useful heat. At smaller scales (typically below 1 MW) a gas engine or diesel engine may be used. Cogeneration is a thermodynamically efficient use of fuel. In separate production of electricity, some energy must be discarded as waste heat, but in cogeneration this thermal energy is put to use. All thermal power plants emit heat during electricity generation, which can be released into the natural environment through cooling towers, flue gas, or by other means. In contrast,

CHP captures some or all of the by-product for heating, either very close to the plant, or as hot water for district heating with temperatures ranging from approximately 80 to 130 ℃.

This means that less fuel needs to be consumed to produce the same amount of useful energy. Small CHP plants are an example of decentralized energy. And as figure 2.2 shows, a CHP unit is turbine-generation based, generate electricity and utilize waste heat to increase efficiency.

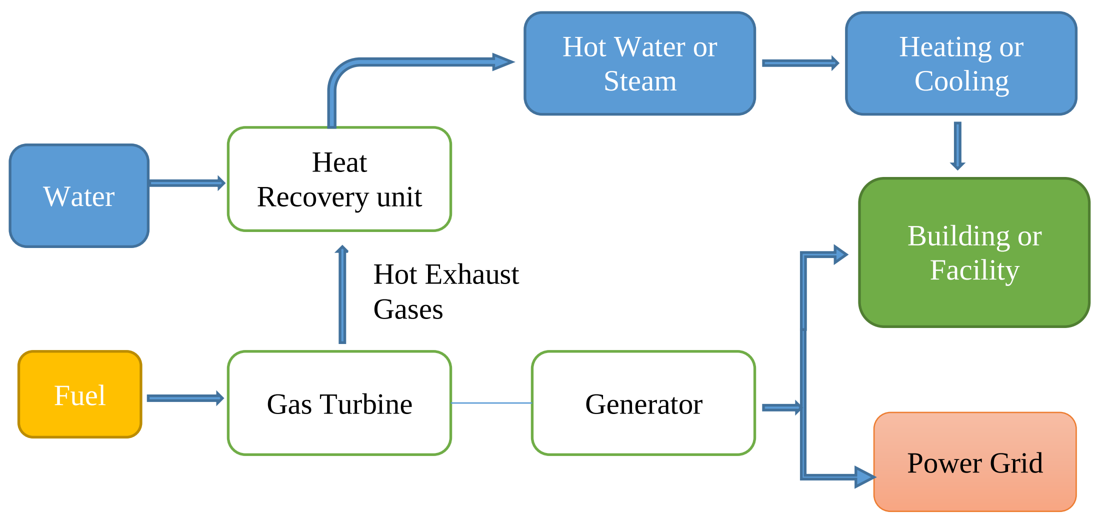


Figure 2. 2 CHP unit energy flow

In the Olney Town project, CHP is modeled together with absorption chiller. A load model is also added, but as a mathematical model to calculate energy, rather than the load models we connect to the main bus as microgrid components.

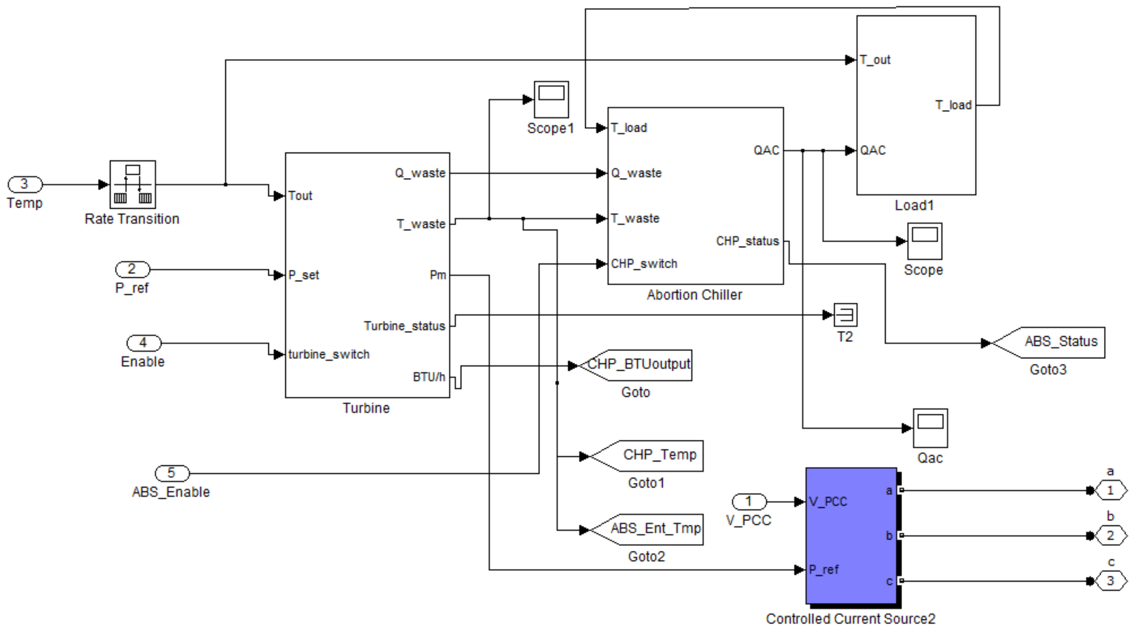


Figure 2. 3 CHP and absorption chiller model

The table below shows all inputs and outputs of the model.

Table 2. 1 CHP inputs and outputs

Model inputs	Model outputs
P_ref: output real power target.	a, b, c: Three phase electricity wavesforms which represent electricity the CHP unit injects into the main bus.
Enable: CHP turbine enable signal.	Parameters of the model which can be measured, like turbine waste temperature, energy in BTU/h, real and reactive power in watts.
ABS_Enable: ABS unit enable signal.	
Temp: ambient temperature.	

2.3.2 Photovoltaic System

A photovoltaic power system is a power system designed to supply usable solar power by means of conversion of solar energy to electric power. It consists of an arrangement of several components, including solar panels to absorb and directly convert sunlight into electricity, a solar inverter to change the electrical current from DC to AC, as well as mounting, cabling and other electrical accessories to set-up a working system.

The PV modeling in the project is currently using real 5-minute measurement solar data to create a solar radiation database. To fulfill the microgrid controller data resolution requirements, the 5-minutes data is resampled to higher resolution using interpolation. The real solar data contain 3 day types: Sunny, Partial Cloudy, Cloudy, allowing selecting solar profiles randomly. Storms and clouds effects can also be added at designated time intervals. Similar to the other components, it is connected to an inverter before connecting to the main bus.

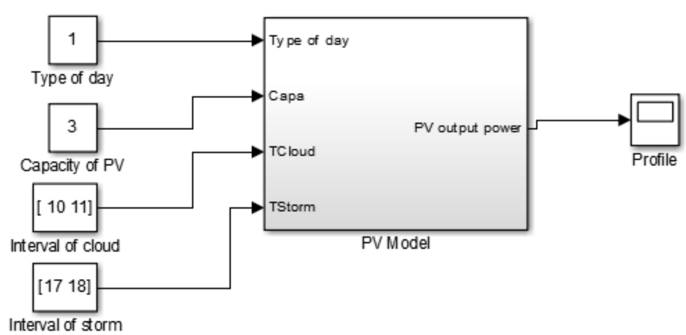


Figure 2. 4 Static PV model using solar data

Figure 2.3 shows the PV model in Simulink, and figure below shows the other part of PV model in OPAL. Existing PV solar data is stored in a file, read into the system by blocks "OPFromFile" in OPAL and fed into the model through user defined input "P_ref". Since the PV model is designed to use pre-defined data, a method is needed to convert these RMS values into real time sinusoidal waves which represent electricity flows in the grid. Figure 2.4 shows how this is achieved. Note this involves converting 1 minute interval RMS values into three phase sinusoidal waves with 120 degree phase difference and same amplitude.

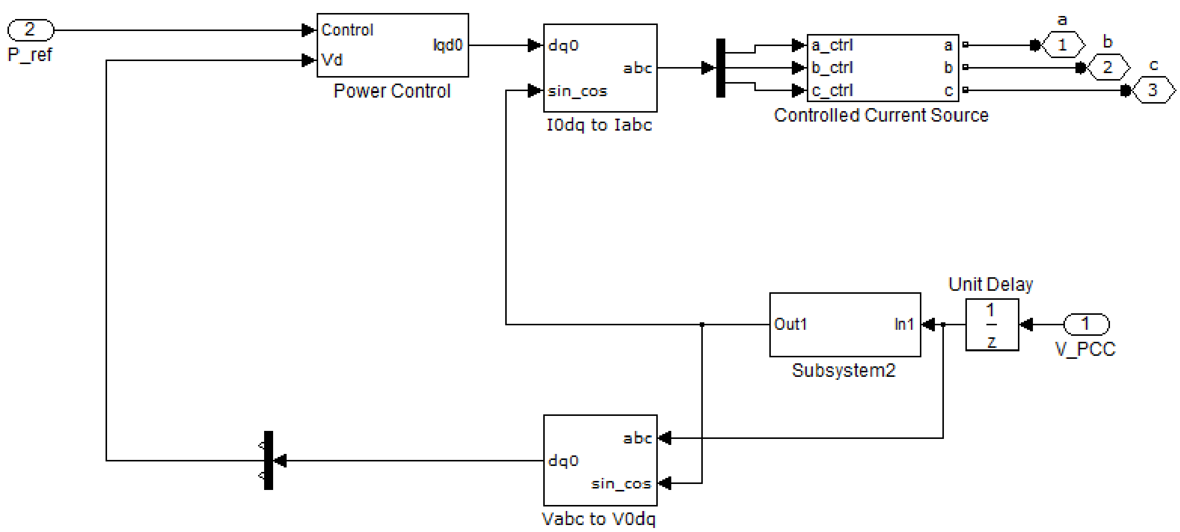


Figure 2. 5 Data conversion scheme

The model inputs and outputs are listed in table 2.2:

Table 2. 2 Photovoltaic model inputs and outputs

Model inputs	Model outputs
P_ref: Solar data.	Three phase electricity flow which fed into the main bus.
Enable: enable signal of the model.	Parameters of the model which can be measured, like voltage, current, real and reactive power.

2.3.3 Energy Storage

Energy storage is accomplished by devices or physical media that store energy to perform useful processes at a later time. A device that stores energy is sometimes called an accumulator. Many forms of energy produce useful work, heating or cooling to meet societal needs. These energy forms include chemical energy, gravitational potential energy, electrical potential, electricity, temperature differences, latent heat, and kinetic energy. Energy storage involves converting energy from forms that are difficult to store (electricity, kinetic energy, etc.) to more conveniently or economically storable forms.

The battery model given by Matlab used to build the energy storage unit in this project. The Battery integrated block in Matlab implements a generic dynamic model, parameterized to represent a few popular types of rechargeable batteries. The energy storage model circuit contains battery is shown below:

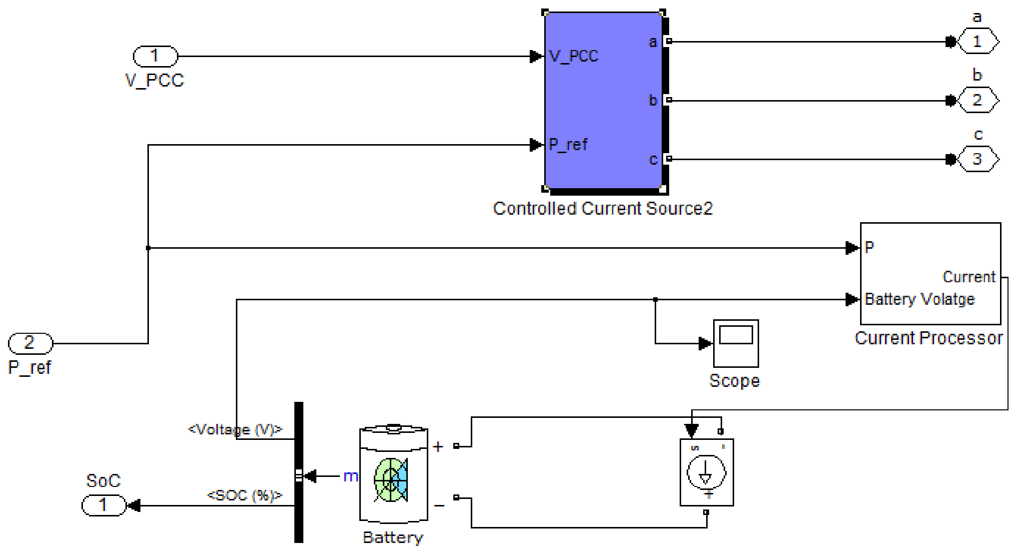


Figure 2. 6 Battery block equivalent circuit in Matlab

Energy storage model inputs and outputs are listed in Table 2.3.

Table 2. 3 Energy Storage Unit model inputs and outputs

Model inputs	Model outputs
V_PCC : Main bus voltage	Three phase electricity feed into main bus.
P_ref: Output real power reference	SOC: State of charge of the battery.

2.3.4 Customer Electric Load Model

There are a number of ways to model loads. In this project lookup tables are used to model static loads performance using utility load data. Since data given by the utility has one-hour resolution, additional 15-minute residential load data based on PNNL field demos are introduced to the model. Similar to the PV model, the hourly data is resampled to get higher resolution using interpolation. The load model is setup for both summer and winter day types, with four load priorities: High, Medium, Low, and Optional. The model allows a random selection of load profiles, which includes modeling of cycling loads such as air conditioning

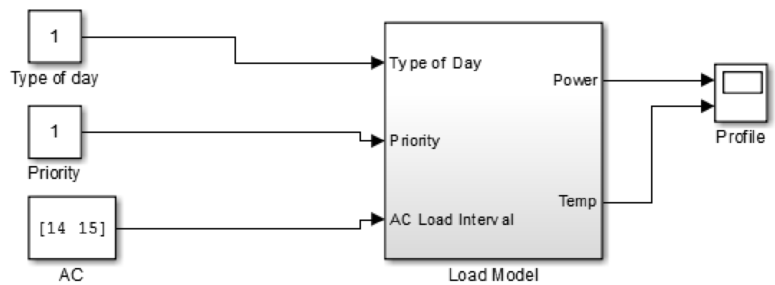


Figure 2. 7 Static load model

The implementation of the load model in this project is similar to the PV model. Pre-defined RMS data is converted it into real time three phase sinusoidal waves and connected with the main bus. Below the figure 2.8 shows how RT-LAB supports us with file reading functionality. And we define load profile data as “Load_Control”, which does not actually “control” load as the name indicates.

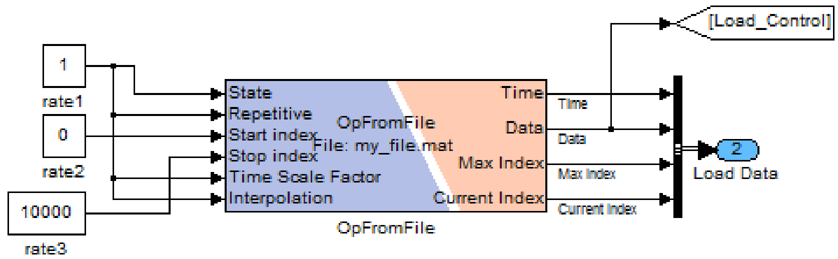


Figure 2. 8 Read file scheme in RT-LAB

Table 2. 4 Load model inputs and outputs

Model inputs	Model outputs
P_ref: Load profile	Three phase electricity wavesforms which represent electricity the load consumed from the main bus
	Parameters of the model which can be measured, like voltage, current, real and reactive power.

Chapter III. DNP3 Protocol and Communication Interface

3.1 DNP3 Overview

DNP3 (Distributed Network Protocol, version 3) is a telecommunication standard that defines communications between master stations and outstations.[5] It was developed by GE, previously Harris, Westronics, and it was based on the early parts of the IEC 60870-5 standard. Today DNP is used world-wide, but mostly in North and South America, UK, Australia, parts of Asia, and South Africa. It's not only used in electric utility grids, but also used in oil & gas and water industry. DNP3 is one of the most popular protocols used by North American utilizes today.

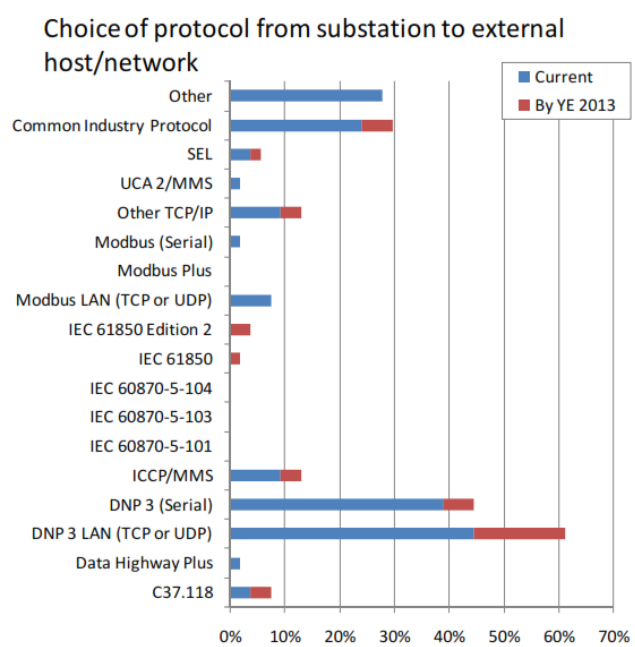


Figure 3. 1 Protocol choice from substation to outside network [5]

Reasons why DNP3 is so widely used is based on the benefits it brings to utilities. As an open standard, DNP3 provides interoperability between equipment from different manufacturers. Users can purchase master stations from one manufacturer and RTU equipment from another manufacturer. Other benefits include:

- Supported by an active DNP3 User Group;
- Widely adopted by large and increasing group of manufacturers;
- It has a layered architecture conforming to IEC enhanced performance architecture model;
- Optimized for reliable and efficient SCADA communications.

DNP3 utilizes three layers of the OSI 7-layers model, called Enhanced Performance Architecture. The three layers are the application layer, transport layer and data link layer. Each layer contains a header which would either help transport the message or indicate functionalities. Data is categorized as class 0, 1, 2 and 3 in DNP3 protocol. Static data, meaning current value of a point, is assigned to class 0. Event data, meaning something significant happens can be assigned to class 1, 2 or 3. Data in class 1, 2 and 3 is also in class 0, meaning that polls for class 0 data actually polls for all classes. The DNP3 protocol does not assign any significance between class 1 2 and 3, they can be defined by users.

Report By Exception is often used in DNP3. That means the outstation reports data changes only, either in response to polling or in unsolicited reporting. “Unsolicited” means the outstation send data changes or events without master station polling, and it's often used when the master station needs to reply on outstation to send specific event data actively.

3.2 Implementation for Project Application

Communication interface in this project contains two parts: DNP3 master station and DNP3 outstation (DNP3 slave). DNP3 outstation interface is integrated into the microgrid model. It responses to master station poll, receives outputs from master station and delivers them to microgrid model. The microgrid controller designed by Green Energy Corporation (namely Green Bus) serves as DNP3 master station in communication infrastructure. Tests referred to in this thesis use another master station developed in LabVIEW platform, and the other protocol test software Protocol Test Harness.

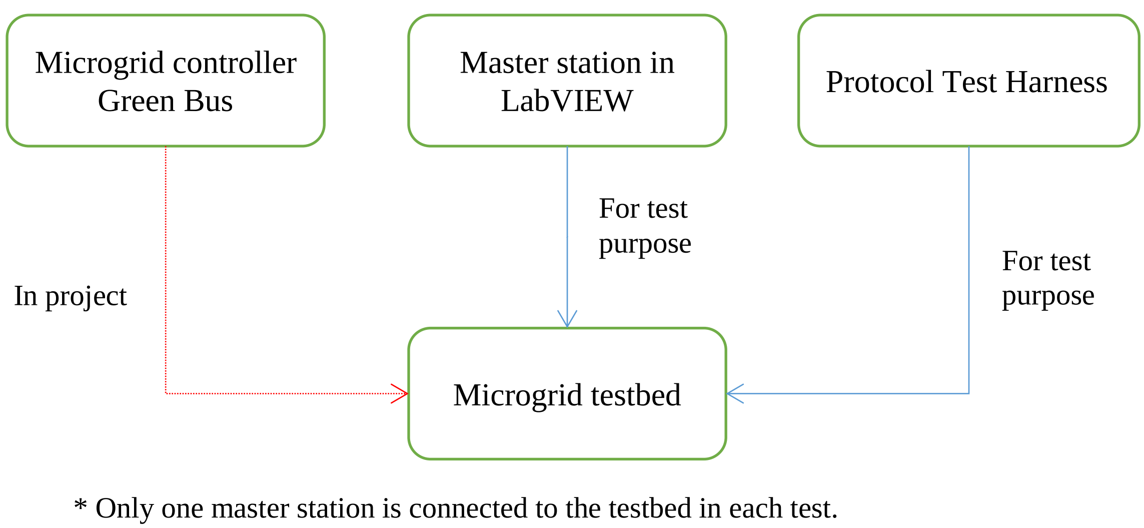


Figure 3. 2 Communication infrastructure

Data transfer between master station and outstation are mainly analog inputs, analog outputs, binary inputs and binary outputs. Analog inputs are signed numeric values, either physical values—like voltage or frequency of the model, or calculated values—like efficiency. Analog outputs are also signed numeric values, but they originate from the master station and often function as setpoints of a desired operating level .Binary inputs are single-bit Boolean type values, usually standing for on or off status. Binary outputs are commonly referred to as Control Relay Output Block (CROB), and in this project we'll use it to control switch and relay to open or close. Unsolicited message is also enabled, to make sure the outstation has the capability to send an alarm signal whenever a value exceeds its pre-defined threshold.

3.3 Communication System Setup

The communication architecture is simple for the prototype system; every test contains one master station and one outstation. In the future we may add a relay to the system, which lies between master station and outstation that will function as outstation No. 2. The prototype system communication architecture is shown in the figure below.

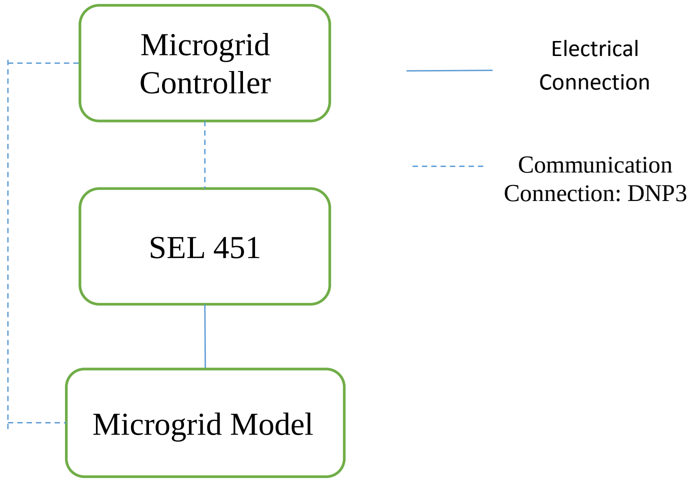


Figure 3. 3 DNP3 communication infrastructure (with relay in loop)

3.4 Master Interface in LabVIEW

A DNP3 master station is designed and developed in LabVIEW to increase the flexibility in system testing. As a graphical automation system design tool, LabVIEW can provide more flexibility in conducting the test and validation process.

The DNP3 master interface is based on DNP3 tool box in LabVIEW. The Virtual Instruments (often referred to as VI in LabVIEW, it's the basic building block of programs written in LabVIEW. It is similar to a function or subroutine in other programming languages) implement DNP3 protocol stacks to achieve its communication functionalities. Master station programming contains various VIs in this tool box to achieve different control commands over DNP3 slave station. The execution flowchart is shown in figure below.

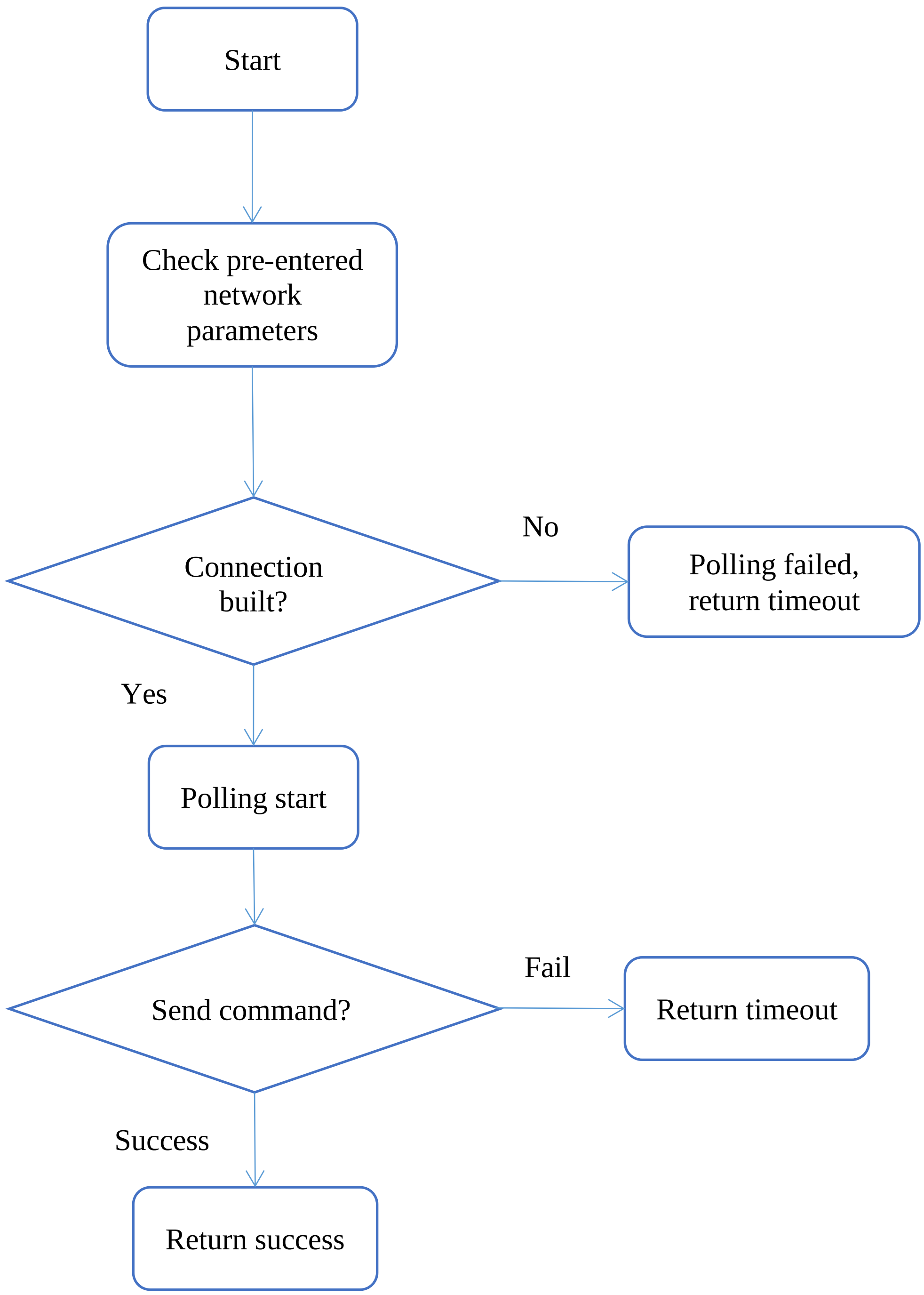


Figure 3. 4 DNP3 master interface flowchart

The programming environment in LabVIEW contains two parts: front panel and block diagram. The front panel is often used as Human Machine Interface in LabVIEW programming, and the block diagram is the programming underneath interface. The front panel is also divided into two parts, DNP3 parameters and microgrid components data. These are shown separately in figure 3.5 and 3.6.

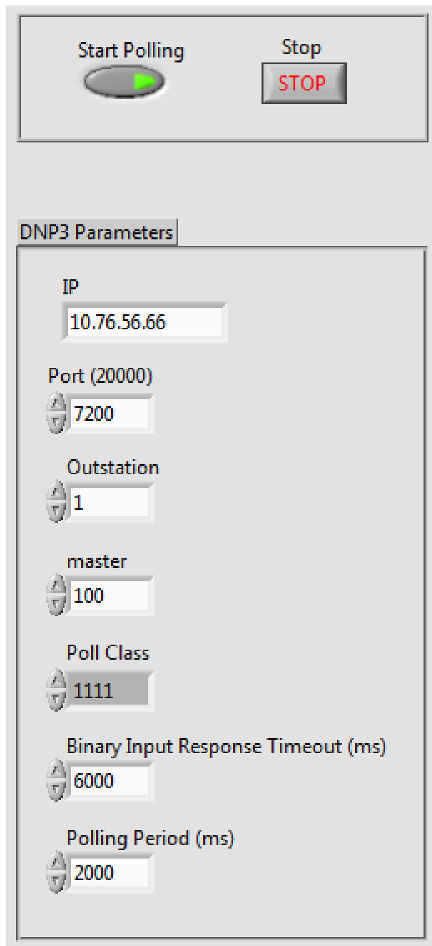


Figure 3. 5 DNP3 Parameters

Figure 3. 6 Microgrid components interface

The components interface is a tab control which contains a few tabs. Each tab contains the data and control scheme of one component. According to the point list given by controller designers group, points with different types will be implemented into these tabs. A prototype interface development is shown in thesis work, and Energy Storage unit tab is chosen to illustrate basic control capabilities of DNP3 master interface in LabVIEW.

The block diagram contains the graphical source code of a LabVIEW program. The concept of the block diagram is to separate the graphical source code from the user interface in a logical and simple manner. Terminals on the block diagram reflect the changes made to their corresponding front panel, often considered as terminals of the block diagram, and vice versa. The block diagram programming will be listed in Appendix C.

Analog inputs and binary inputs are shown in the top-left corner in Figure 3.6. Binary inputs are referred to by indexes and indicated by light indicators. Analog inputs are located by indexes and shown by numeric values, and charts are also used to show the trending and part history data of analog inputs. Setpoint control is analog output control in DNP3, which sends out analog values as setpoints to the slave station. Relay control, or CROB (Control Relay Output Block), is binary output in DNP3. It's used to control breakers and other parameters which only have two statuses.

Detailed communication tests and results will be shown in Chapter VI.

3.5 Slave Interface in OPAL-RT

The microgrid model in RT-LAB acts as a DNP3 slave device (outstation). It should be capable of providing the DNP3 master with proper interface of DNP3, as well as all points the master will need to poll for. This communication function and appropriate outputs points for the model are one part of it, called DNP3 slave interface. It consists of one asynchronized DNP3 block, and all analog and binary points.

3.5.1 RT-LAB DNP3 Block

RT-LAB has one block designed for simple DNP3 communication as a slave station, and it's shown below.

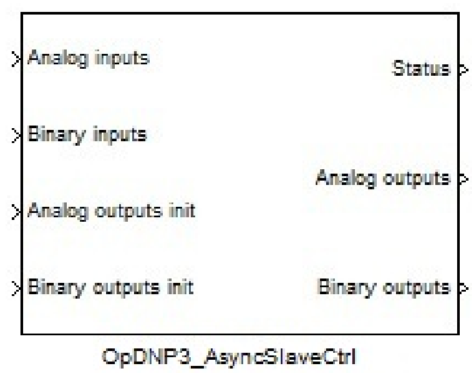


Figure 3. 7 DNP3 block in RT-LAB

To prepare the model with DNP3 capability, two parts of the configuration should be identically set. One parameter setting location is the property block of the OpDNP3 block. By properly configuring block properties, like IP address, port number for two sides of the communication, and other essential parameters, we can get the slave device ready to be polled. Another location is an XML file as it provides above and more complete information of the connection. The IP address can be chosen based on meeting following criteria:

a) Within the same subnet of hardware IP and

b) It is not used by other devices.

The value “Configuration file name” in property block should correspond to the real XML file name located in the project folder.

3.5.2 Points List

When setting the block, one thing of great importance is the number of inputs. Drawing model outputs and feeding them into the block should also be done manually because the block does not get the values automatically. To appropriately prepare the model with matching interface, we need to know what points are designed to feed the microgrid controller and thus build the corresponding points into the model. Points are divided into four categories: analog input (AI), analog output (AO), binary input (BI) and binary output (BO). Outputs are control commands like trip/close, set points. Inputs are measured physical values, predefined ratings or status. No counters are involved in the project at this phase.

By checking the microgrid design files and meeting with controller designers, a complete points list and meaning of them are found and implemented into the interface. Below is the complete point list and implementation status for the Point of Common Coupling. See Appendix A for full points list of other units and their meanings.

Table 3. 1 DNP3 Points of Point of Common Coupling*

Added?	**Name**	**Type**	**Unit**	**Comment**
Y	kW	Analog Input	kW	This is the measured power come from whole grid. Positive value stands for power consumed by microgrid, and negative power means power flow from microgrid to whole grid.
Y	kV	Analog Input	kV	Voltage at Point of Common Coupling.
Y	Amps	Analog Input	A	Current at Point of Common Coupling.
N	PwrFact	Analog Input		Power factor of power.
N	Hz	Analog Input	Hz	Frequency at Point of Common Coupling.
N	Status	Binary Input		Status of this Point of Common Coupling, open or closed.
N	Trip	Binary Output		Trip the breaker.
N	Close	Binary Output		Close the breaker.

* PCC_Head and PCC_Tail have the same point list.

3.5.3 Slave Device Interface

The whole microgrid simulation model is divided into two subsystems: SM_Master and SC_Console. When loading the model to target hardware, these two subsystems are loaded into different cores and can be run in various time steps. Only scopes in SC_Console are able to show the user real time data. The feature of showing real time data is crucial to communication testing, thus the DNP3 interface in model is assigned to both subsystems. Communication testing is the first step before executing any other tests, to ensure the model has sufficient communicating capability. This test should include two parts, substantiating the interface is capable of supporting DNP3 in two directions—both receiving and transmitting data. This testing will be further discussed in Chapter 6.

The asynchronized DNP3 block is put into SM_Mater subsystem, and some of the points are sent to the SC_Console. Figure 3.8 and 3.9 show how the interface is arranged in the two subsystems.

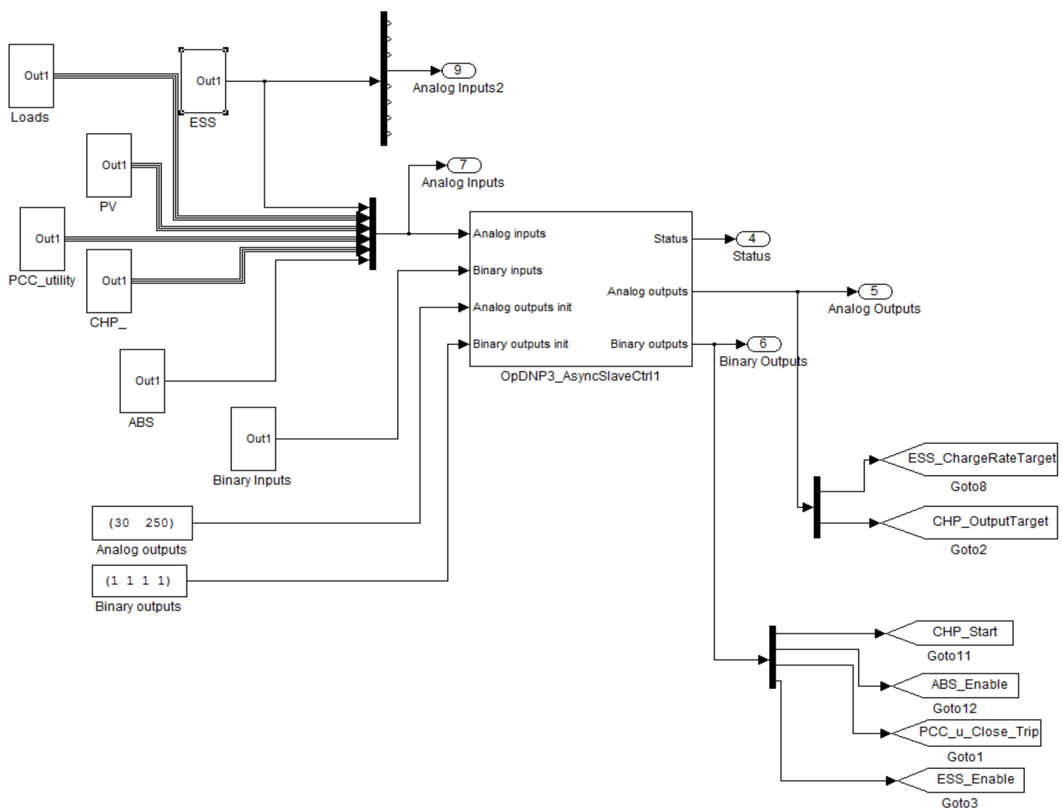


Figure 3. 8 DNP3 slave control in SM_Master

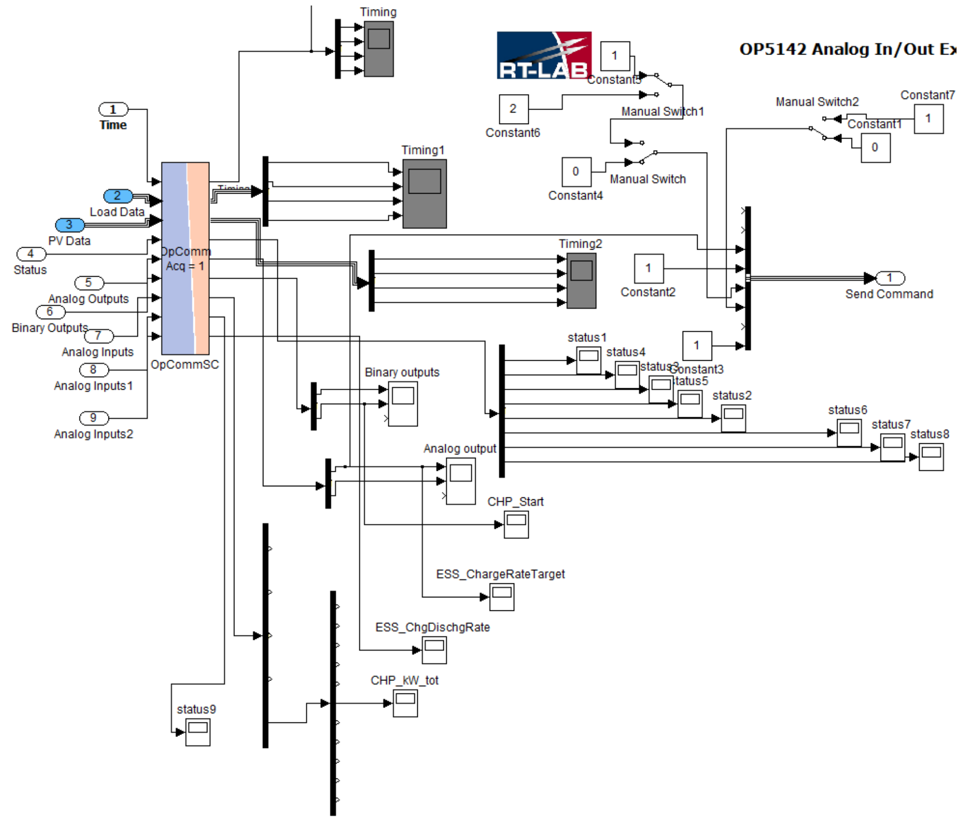


Figure 3. 9 DNP3 interface in SC_Console

Chapter IV. Microgrid Controller Use Cases and Simulation Validation

After introducing models for different components and communication part in the microgrid simulation system, it's necessary to further understand and discuss the design behind them from controller stand of point. Also, simulation validation is needed to convince the built of models meet our original designing goal.

4.1 Microgrid Controller Functionalities

The microgrid controller is designed to maintain voltage and frequency to a pre-defined level, as well as managing energy and securing microgrid islanding operation mode. For the energy management function, the central controller optimizes the power microgrid exchanges with the whole electric grid, maximizing the local production from distributed energy resources depending on the market prices and security constraints. It is achieved by issuing control set points to distributed energy units and controllable loads within the microgrid. The communication can be through Ethernet, power line carrier, or wireless network. Normally the controller makes decisions for a specified time intervals such as every 15 minutes for the next hours or a day. [7]

The special problems a microgrid controller may encounter are control during islanding operation or transferring between islanding and non-islanding operations. Due to adverse weather or other severe faults, the whole electric grid might go down and thus the microgrid may need to disconnect from it and maintain its own normal operation. Or in another situation, where the microgrid goes down along with the whole grid, it will need to support the community within the territory by initiating a blackstart. Voltage and frequency control are two key problems during a blackstart. After the microgrid is operating successfully in an island mode and the whole grid gets back to normal, the microgrid may need to reconnect to it. This is where the problem of transition from island to grid-connected introduced. A microgrid central controller needs corresponding strategies to deal with all problems above.

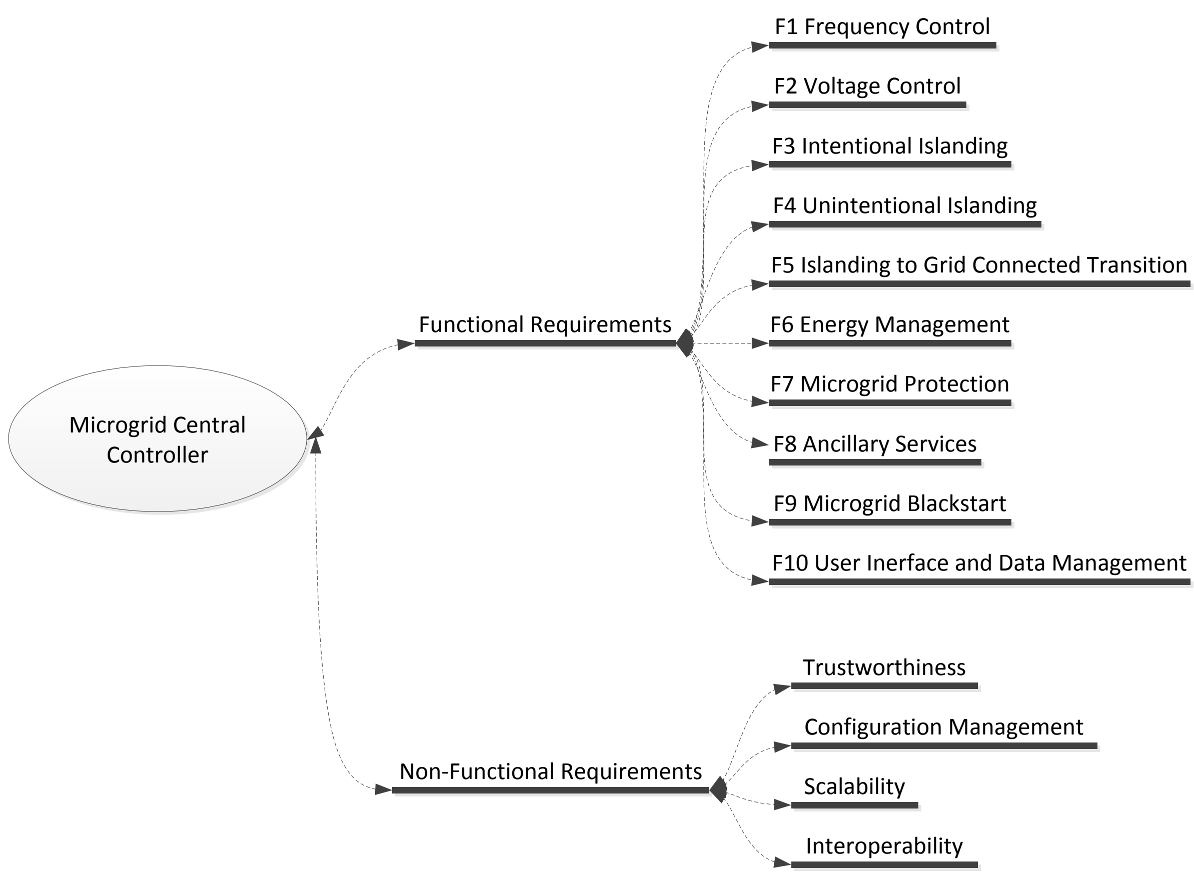


Figure 4. 1 Green Energy Bus functionalities

Figure 4.1 illustrates requirements that drive microgrid controller functionalities. These requirements are divided into two categories: Functional and Non-functional. Functional requirements are described briefly in the above paragraph, and they are considered and designed to achieve the control capability over a microgrid. Non-functional requirements are based on the consideration that it's at the same time software which should be easily managed, maintained and implemented into the whole control system without causing any security problems.

4.2 Use Cases

Electric Power Research Institute (EPRI) proposed several microgrid functional user cases as a guide that shows how the controller should accomplish these important functionalities. These use cases are adopted by Green Energy Corp in microgrid controller design.

These use cases include: Frequency Control, Voltage Control, Intentional Islanding, Unintentional Islanding, Island to Grid Connected Transition, Energy Management, Microgrid Protection, Ancillary Services, Microgrid Blackstart, User Interface and Data Management. The use case this project is most concerned about is the Energy Management user case. Through validating the controller's capability on this user case, this project can meet the energy efficiency enhancement requirement proposed by DOE.

4.2.1 Energy Management

The microgrid Energy Management System (EMS) is an important part of the microgrid controller, which provides an interface between the Distribution Management System (DMS) and the microgrid. The microgrid EMS manages the power flow, power transaction, energy generation and consumption, voltage/reactive power, and battery charging/discharging in a microgrid. The objective of the Microgrid EMS is to coordinate among multiple DERs, storage/battery, main grid and responsive loads to improve the system reliability and reduce the total operation cost.

The optimization objectives are achieved by deploying a three-stage energy management: Day ahead Bidding and Scheduling, Short-term Economic Dispatch and Real-time Optimal Power Flow (OPF).

The Day-ahead Bidding and Scheduling stage includes the function of day-ahead operation planning. The plan is developed on the day before the actual operation, and can be updated on the day of operation. It contains the optimal bidding and scheduling plan for electricity and heat (at hourly interval) for the next day, based on the demand forecast, renewable DER output and market prices. Normally, in developing this plan, the unit commitment status and output dispatch of DERs and the power purchased/sold in the day-ahead market are determined, minimizing the fuel and environmental cost. The Short-term Economic Dispatch develops the optimal short-term dispatch of electricity and heat scheduling plan in 5 or 10 minutes intervals for the next hour. Through this function, the gap between day-ahead forecast results and the short-term (hour-ahead) forecast results of the planned output are filled. The Real-time Optimal Power Flow (OPF) develops an operational plan for a 1 minute interval between two short-term economic dispatch intervals. The variation of demand and renewable DER output is compensated by executing this function.

4.3.2 Microgrid Blackstart

After a complete shutdown, blackstart is executed to restore the microgrid which is in island operation mode. The process involves the microgrid central controller, distributed resources, loads, and multiple circuit breakers. The blackstart procedure can be pre-determined and implemented in the microgrid central controller and other devices based on the system topology, sizes of resources and loads. There a few main steps involved in the execution of the microgrid blackstart.

Microgrid controller initiates the blackstart procedure first by checking if the microgrid switch at PCC (point of common coupling) is open or not. If the microgrid is not completely disconnected from the main grid, a command will be sent to the microgrid switch controller to open the switch. Then the primary source and its matching loads (or primary loads) need to be isolated from the rest of the microgrid by similar process conducted above. A primary source, mainly defined by its capability of control over voltage and frequency, should be restored with loads matching its capacity for the next step. The primary source starts operation by feeding loads and controlling frequency and voltage in specified ranges. Then other resources and loads are added on following a pre-determined order, based on their real and reactive power generation (or consumption). After the whole microgrid is restored completely, it will be operated in the normal islanded mode. At this point the microgrid controller can check the status of both microgrid and area power system to determine whether the microgrid will resynchronize and reconnect to the main grid or remain in islanded operational mode.

4.3 Simulation Validation Methodology

Figuring out a fundamental methodology of simulation validation is especially important where the credibility of a simulation model is crucial. In such cases decisions need to be made in complex situation, or where simulations can provide incentives for decision maker either due to lack of access to the real system or as a sort of prior assessment. In other situations, it is important to understand the potential risks involved when using a simulation: A simulation model may not adequately represent the real world system; the data used may be inaccurate; or it may not be practical to model the exact operational environment. Even the output data gathered to build the model may be flawed in some way or somehow misinterpreted. [16] Either way, a certain quality assurance of the model is needed, and simulation validation, as a way of checking and providing this assurance, is brought out and studied. [15] It will also support decisions on basic concepts, system design, and feasibility of operation without the expense of developing prototypes or test models.

To introduce basics of simulation validation, we need to consider several basic features of simulation. Simulation is the process of a) constructing a model of a system, and b) conducting experiments with the model for a specific purpose of experimentation, such as to solve a problem. Credibility of simulation results is not gained solely by model correctness, but also is significantly influenced by the accurate formulation, or way of implementing the aimed problem into the model. [13] For example, to study the dynamics of a load, a static load model—no matter how correct it it—is not sufficient.

Simulation studies of power systems can be dated back in 1960s, but the importance of its validation and assessment was not noticed until the model actually failed and caused huge loss—known as the WSCC system outage on August 10, 1996, where the failure of simulation in reproducing the dynamic behaviors prior to real system implementation was considered to be one main cause. [14]

In the Olney project, microgrid model simulation is conducted to accomplish the goal of controller testing and demonstration. And since we understand importance of simulation validation, we want to show our model is capable of supporting the tests in developing simulation validation.

Though we use the term "simulation validation" a lot in this thesis, the whole concept is often referred to as "simulation validation and verification" in a lot of references. And here we should briefly differentiate two different definitions between verification and validation. In model validation, we substantiate that the input-output transformation of the model has sufficient accuracy in representing that of the system, or in other words, it deals with building the right model. Often it is conducted by running the model under the same input conditions that drive the system and by comparing model outputs with the corresponding system outputs. Unlike validation, model verification deals with building the model right. It is a process which substantiates that the model is transformed from one form into another with sufficient accuracy. [13]

Due to differences in simulation fields, aiming application, and various simulation methods, we do not yet have a quantitative measure of the level of validation performed on a simulation model. However, there are some principles to consider when conducting simulation validation type of research.

First, the simulation validation and verification study (will be referred to as simulation validation in following content) should be conducted throughout the entire life cycle of the study. It's not a step which we can ignore once we complete it, but a continuing process to correct errors and enhance the model. Second, a simulation model is built with respect to the study objectives, so its credibility should only be judged with respect to those objectives. And similarly, credibility of a simulation model can only be claimed in the prescribed conditions in which the model is built and tested. And normally this study of simulation validation is conducted by different researchers other than the model developer, in order to prevent any intentional or unintentional bias. And last but not least, credibility given by each submodel does not guarantee overall model credibility. [13] They should be tested separately.

From the discussion given above, it's not difficult to see that we need to verify and validate the microgrid model. Can it represent the nature of the real entity in aspects that are of concern? Will it be able to support tests designed to examine corresponding microgrid controller functionalities defined in user cases? And if answers of these questions are yes, what tests should we conduct to ascertain effectiveness of the microgrid model to make sure it has these features? These questions will be further discussed in the following chapter.

Chapter V. Microgrid Model Tests

5.1 Single Model Test Plans

The first thing to do in model validation is to make sure every single model works fine. Thus we need to fully understand how the model works, then test if it performs as designed and expected.

One important feature of each model that needs to be tested is the energy output. Test results are shown in the following sections to justify models capability to generate reasonable output. One assumption made to examine the power flow is that, for a given unit, minus power output means it's absorbing power, and positive output means it's providing the main bus with power, either real or reactive.

5.1.1 Load Output Verification

The load model is tested in whole as an aggregation of all loads, including loads at different priority levels. Figure 5.1 is how the scope block is put in the model, and which outputs are tested. Real time RMS value of real power, current, voltage and reactive power are shown in Figure 5.3 in sequences. One thing needs to be noted is that one transformer is put inside the load group, so the voltage is on primary side and higher than that at load level.

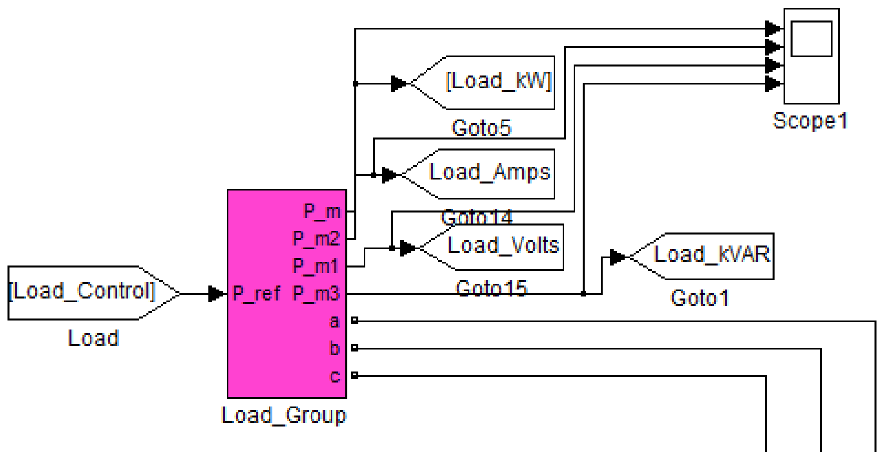


Figure 5. 1 Load group test setup

Figure 5.2 shows the 24-hour load profile used in this test. At the time the scope screenshot was taken, the real power value should be equal to the value found in this profile at the same time.

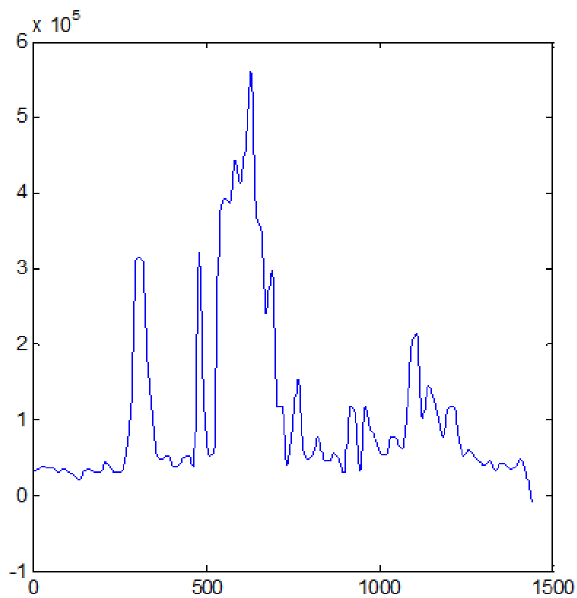


Figure 5. 2 Load profiles of 24 hours (1 minute interval)

From the result shown in Figure 5.3, we can see the real power is 32.84kW at time 6.05s, which is very close to the valure found in the load profile at about the same time. Also the product of voltage and current is 11911.62W, which is very close to one third (load is designed to be balanced) of the square root of $(P^2 + Q^2)$, 13.923kW in this case (small error is allowed since the value is read directly from the figure). Thus we can say the load model is operating normally as expected.

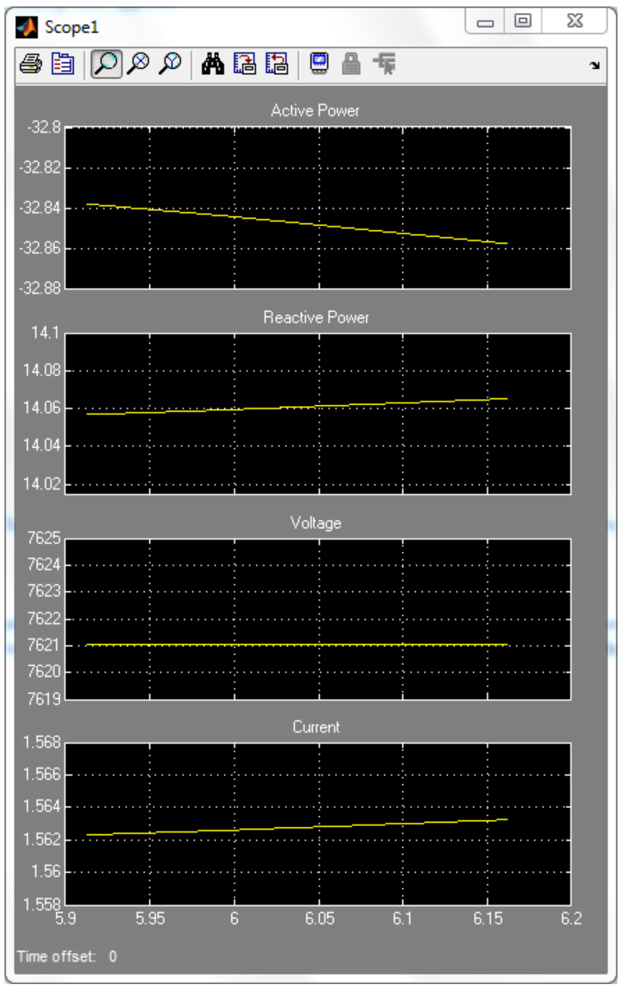


Figure 5. 3 Load group test result

5.1.2 Photovoltaic Model

Similarly, PV model validation is done by checking power output read in the scope, and comparing the value with the solar profile at the same time.

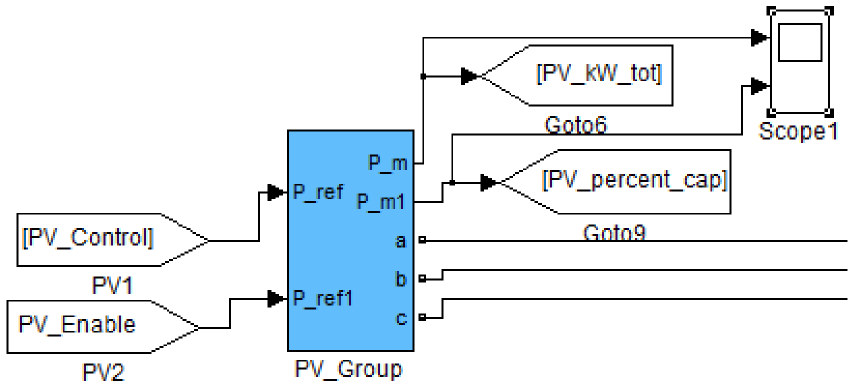


Figure 5. 4 PV group test setup

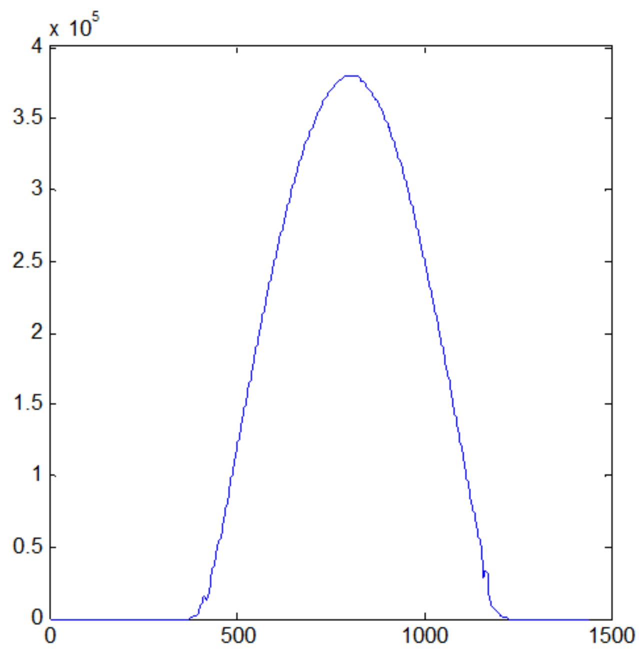


Figure 5. 5 Solar profile

The start point of the test is chosen to be index 500 since there's not much output power before this index. The screenshot of PV output shows PV power output in kW and the percent of output to capacity. At time 3.6s, a time stamp relative to the start point chosen when conducting this test, the output is 122.6kW. It's found out that similar value in the figure at the same time (around index 503.6) in solar profile. Thus the model operates normally.

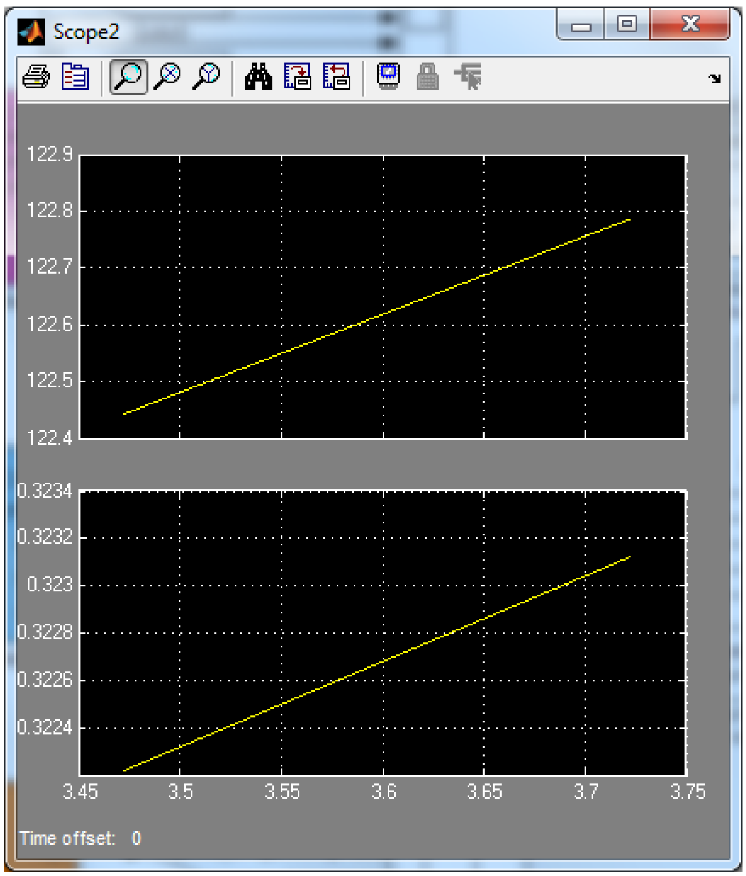


Figure 5. 6 PV output of real power and % output

5.1.3 Energy Storage Unit Model

Testing the energy storage unit is performed by comparing the power output and charge/ discharge rate with the predefined output target. A constant 25 kW is given as the output target for the ESS unit to achieve. From the second subplot in the screenshot of scope, we can see that the actual output rate is very close to this target. So the ESS unit model meets our expectation for testing by far.

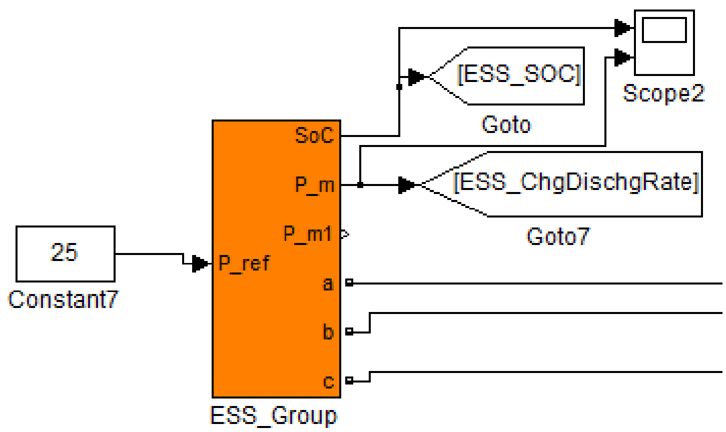


Figure 5. 7 ESS unit test setup

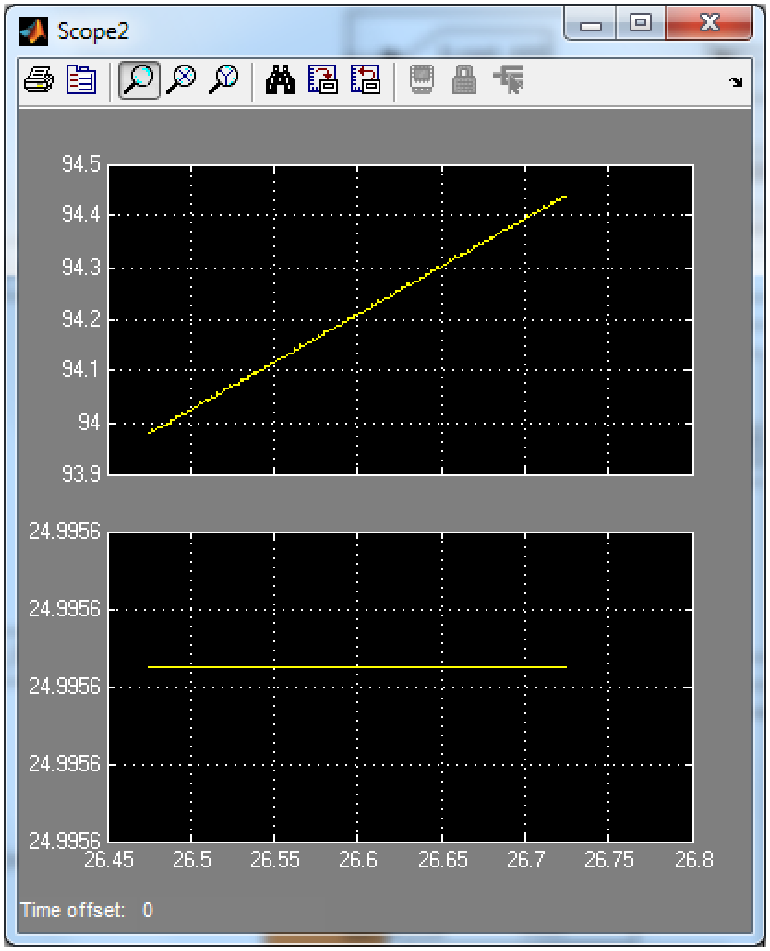


Figure 5. 8 ESS outputs of SOC and Charge/Discharge Rate

5.1.4 Combined Heat and Power and Absorption Chiller

A test similar to ESS validation is used in the CHP model test. Pre-defined constants are fed to model inputs, and the output is measured and compared with the constant.

For the CHP model, the actual output power is measured and compared with the output target, 250kW in this case. A screenshot of the output shows a result of 249.96 kW, which is close enough to say the CHP output can be controller as expected.

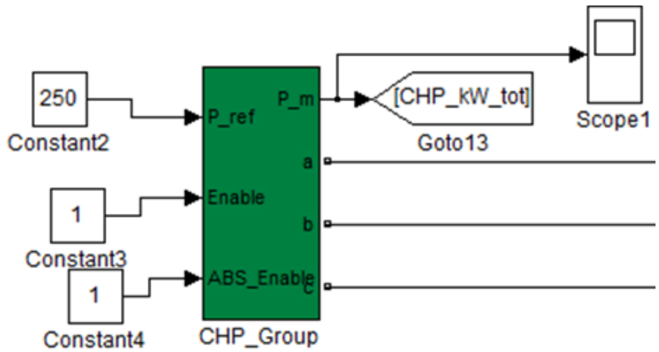


Figure 5. 9 CHP model setup

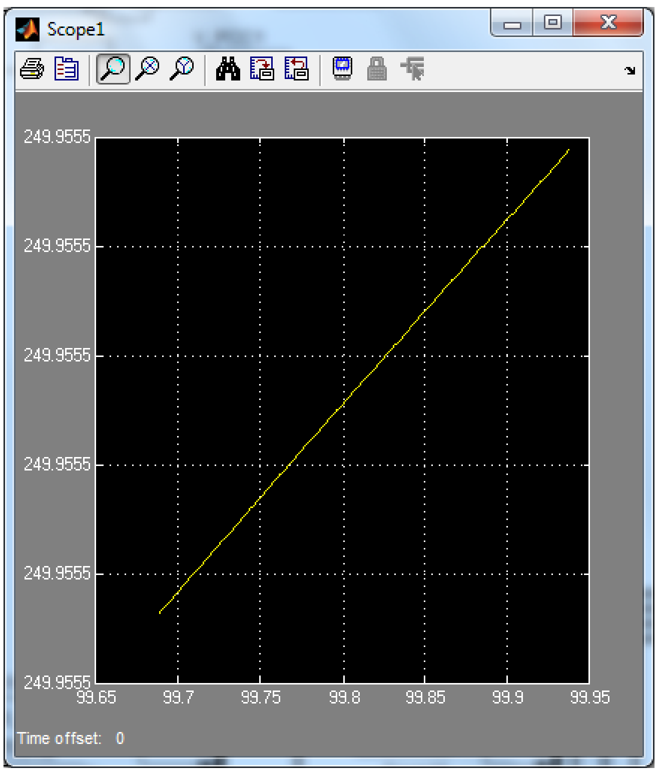


Figure 5. 10 CHP output power

Another output for the CHP unit to examine is the waste heat temperature. A pre-defined limit is 185 degree Centigrade, which is 365 degree Fahrenheit. The screenshot below shows the real waste temperature, which falls within the limitation of 365.

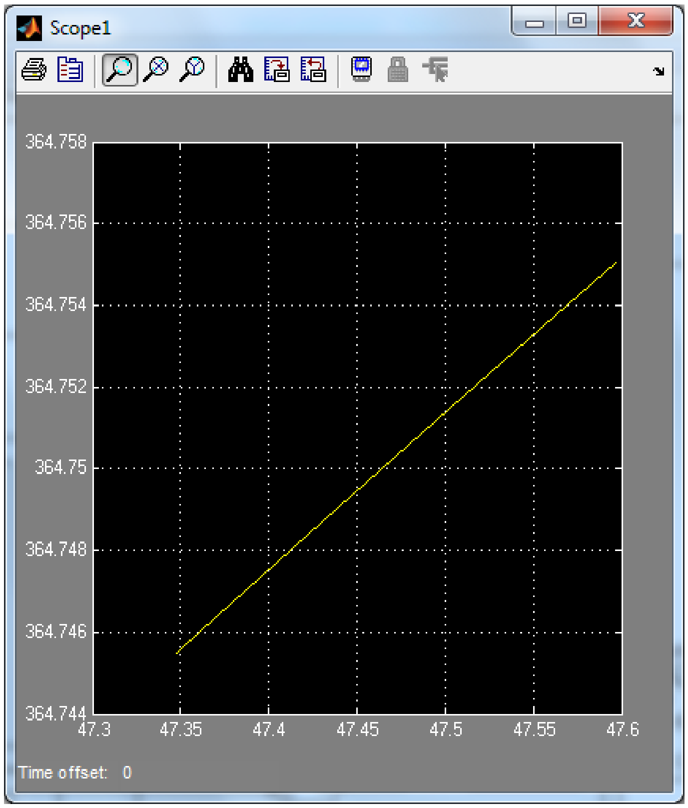


Figure 5. 11 CHP waste heat temperatures

5.2 FREEDM Zone 1 Microgrid Power Flow Test

Having each individual model working fine independently does not guarantee the whole microgrid model works. A test which aims to validate the whole model needs to be conducted.

The test is done in FREEDM test system zone 1. Unlike zone 0, zone 1 contains more units, including 10 loads and 3 PV units, one unit for CHP, ABS and ESS. Power flow should be measured and checked for aggregated groups, which means all loads are monitored as one load group, and PVs are measured in this way also.

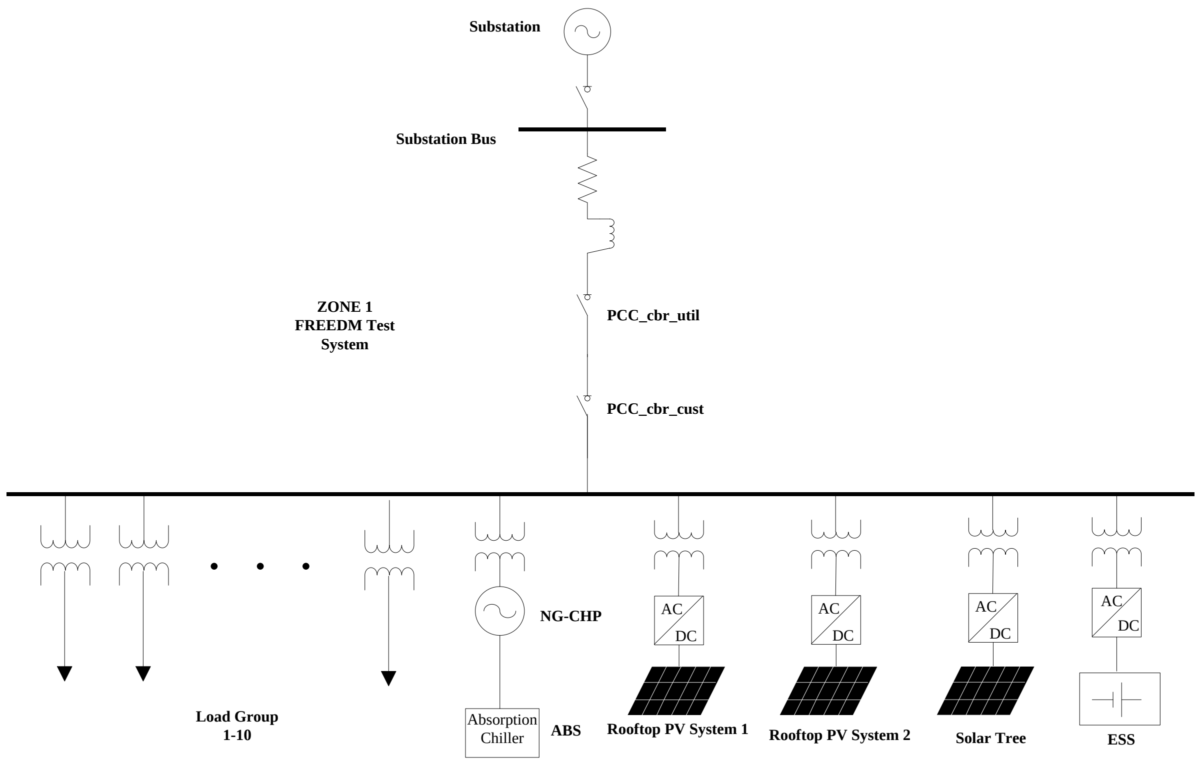


Figure 5. 12 FREEDM Test System Zone 1

By running the system and displaying all real and reactive power provided by all components, fed by whole grid at PCC and line loss between main bus and all components, we can calculate if the sum of electricity generated by microgrid matches the power measured at PCC. The table below shows the measured value and their sum.

Table 6. 1 Power flow result 1

	Real power (kW)	Reactive power (kVAR)
PV	0	0
ESS	25	0.4712
CHP	189.1	3.565
Load	-33.14	-14.19
Line loss*	-1.883 $\times 10^{-4}$	0
Sum of microgrid generation	180.96	-10.06
Power injected to microgrid	-181	10.15

* Line loss is calculated by equation $3(I^2 \times Z)$, where I = 7.923 A and Z = 0.001Ω, and minus stands for power consuming.

Table 6. 2 Power flow result 2

	Real power (kW)	Reactive power (kVAR)
PV	121.2	2.284
ESS	25	0.4712
CHP	80.65	1.52
Load	-32.65	-13.97
Line loss*	-2.164 $\times 10^{-4}$	0
Sum of microgrid generation	194.2	-9.695
Power injected to microgrid	-194.2	9.699

* Line loss is calculated by equation -$3(I^2 \times Z)$, where I = 9.493 A and Z = 0.001Ω, and minus stands for power consuming.

From the test results listed in the two tables above, one can see that sum of microgrid generation equals to the power microgrid fed into the whole electric grid (error is within acceptable range). Thus it can be concluded that the whole microgrid model is working for steady-state dispatch conditions.

Chapter VI. Communication Tests and Results

Communication capability is one important feature the model needs to provide, and is not examined in previous model tests. As planned in the project, DNP3 protocol needs to be implemented and tested. This chapter mainly focuses on communication test, in other words, DNP3 communication tests design and examination.

Two DNP3 master stations are used in the test. Protocol Test Harness is used to test DNP3 functionalities of microgrid testbed. After the testbed is checked for slave station capability, the LabVIEW master station is tested using testbed to prove its DNP3 master station capability.

The reason to arrange tests for LabVIEW is that it can provide more flexibility in exercising future tests. Potential benefits include test automation and history recording. For example in energy dispatch test, the OPAL simulator may need to run for a whole day. In this case it's not possible to manually send all dispatch commands in pre-defined time schedule. So an automated commands sending scheme is crucial. On the other hand, OPAL has a limited storage capacity, leaving the role of data recording to master station. LabVIEW master station is on another computer which has enough storage. The LabVIEW platform is also more flexible in data logging format.

6.1 Master Station Test Tool—Protocol Test Harness

Protocol Test Harness [6], developed by Triangle Microworks, is a powerful tool for testing DNP3, IEC 60870-5, and Modbus devices. It can simulate master or outstation devices in different communication protocols, and run in monitor mode. Test Harness is also capable of creating custom functional tests with any .NET programming language, and performing conformance test procedures as well.

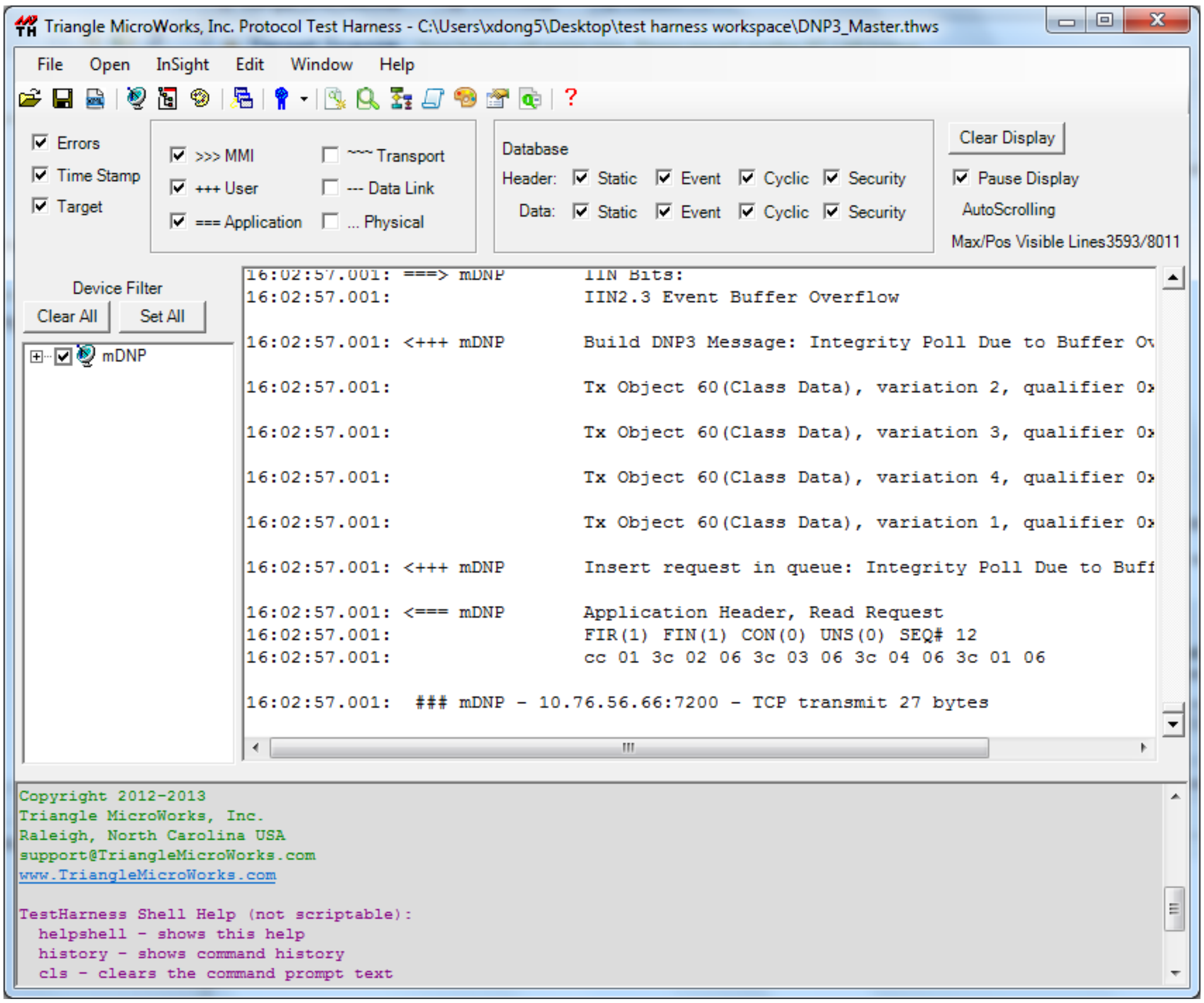


Figure 6. 1 Main interface of Protocol Test Harness

In this project, this tool is used to simulate a DNP3 master to test the communication capability of the model, so a connection between Test harness as DNP master station and microgrid model as DNP outstation in RT-LAB is built. On configuring the outstation with proper IP address, port number and link layer addresses (which was discussed in Chapter 4), the microgrid testbed is prepared by loading the configuration files. Then the corresponding parameters of DNP channel and session are input into Test Harness to build a new workspace. Figure 6.1 shows the main interface when the DNP3 connection is established between master and outstation.

Test Harness is capable of sending commands as well as polling data based on class via its command window. The DNP command window can also enable/ disable unsolicited messages and send time synchronization signal. These functions are checked in the tests, since the DNP slave control block in RT-LAB claims to support all of them.

6.2 Communication Tests and Results

Communication tests are divided into different parts to check for different functionalities. First and foremost, data exchange tests are conducted to ensure the slave device can receive commands, both analog and binary, and operate following these commands. Also the test checking if the slave responses to polling commands from master station is executed. By confirming all of them work fine, the communication path as well as model control capability are verified. Then functionality like time synchronization and unsolicited message are tested.

6.2.1 Data Exchange Test

To make sure the model responds to analog outputs, both the data received and corresponding response need to be checked. As is shown in Figure 6.2, analog output initial values are received in Test Harness. The verification is done by sending analog outputs using Command Window and checking results in the model.

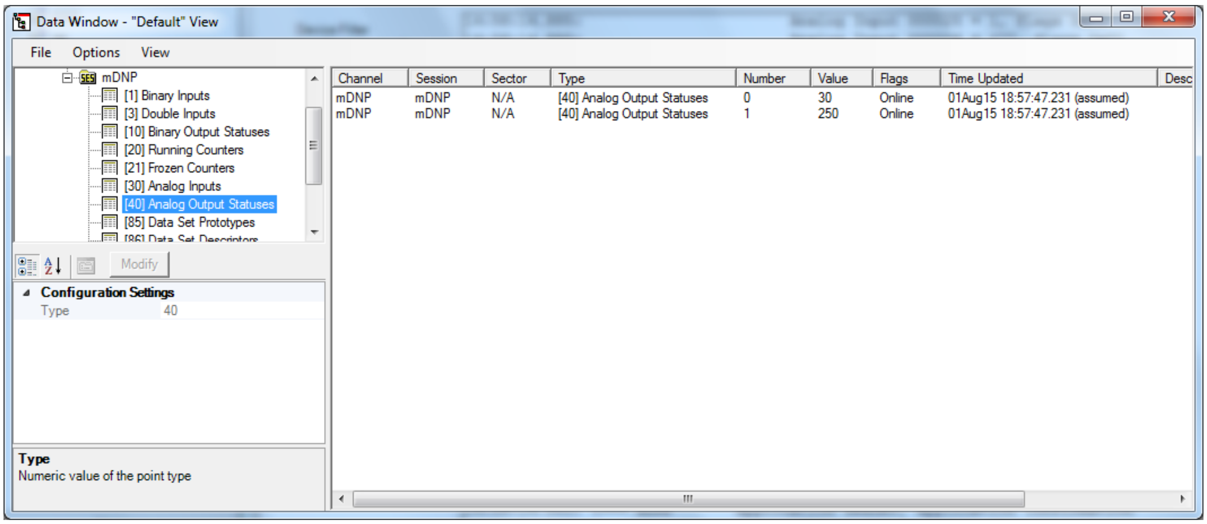


Figure 6. 2 Analog output initials received in Test Harness

The analog output point chosen to test is “ESS_ChargeRate Target”. This is the output target of the energy storage unit, and analog input point “ESS_ChgDischgRate” is the real output of energy storage unit, which in all cases should be consistent with “ESS_ChargeRate Target”.

First change the value of “ESS_ChargeRate Target” from the command window, then checking this value received in outstation. Secondly the real output is checked to see if the model is capable of supporting analog output.

Figure 6.3 shows real time value measured in the model in initial conditions, where the output target is 30 kW.

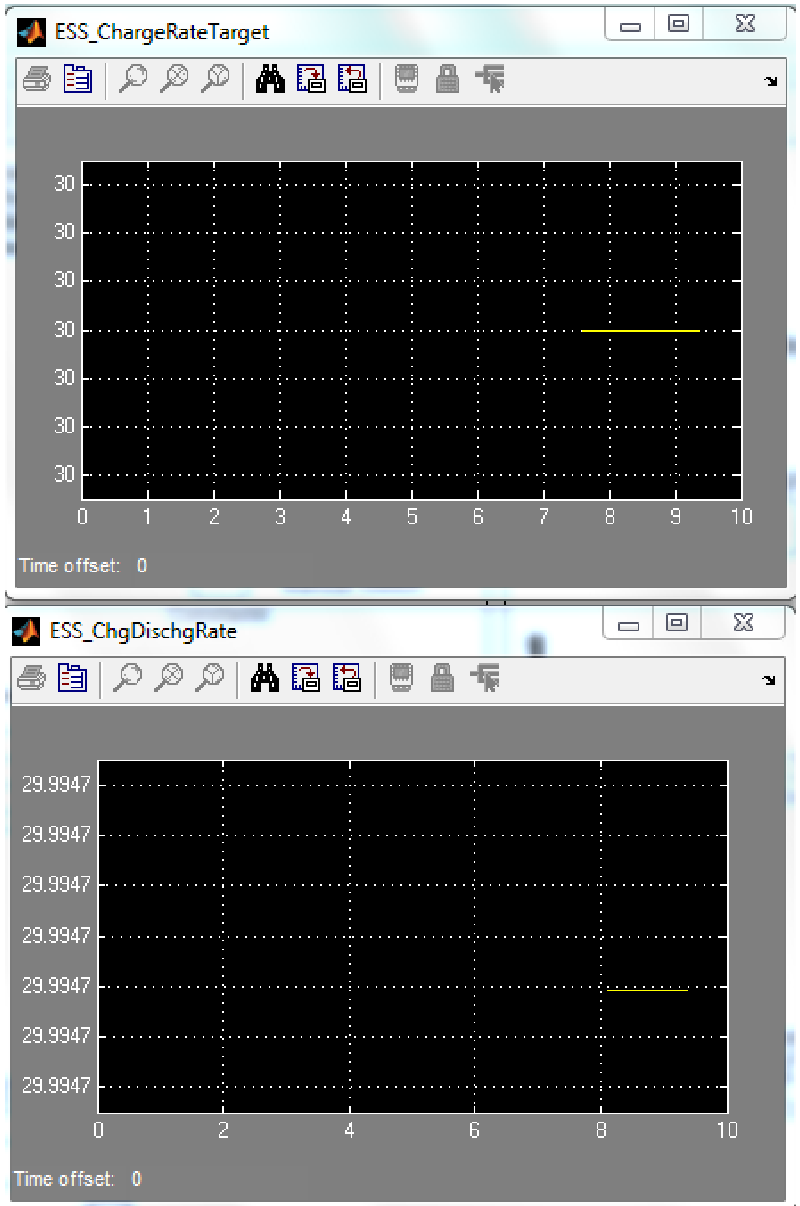


Figure 6. 3 ESS_ChargeRate Target and ESS_ChgDischgRate values in initial condition

The analog output of the charge rate target, with value of 3500 kW is sent through the command window with result shown in Figure 6.5. Though a small error exists, the outstation function to response to analog output is validated.

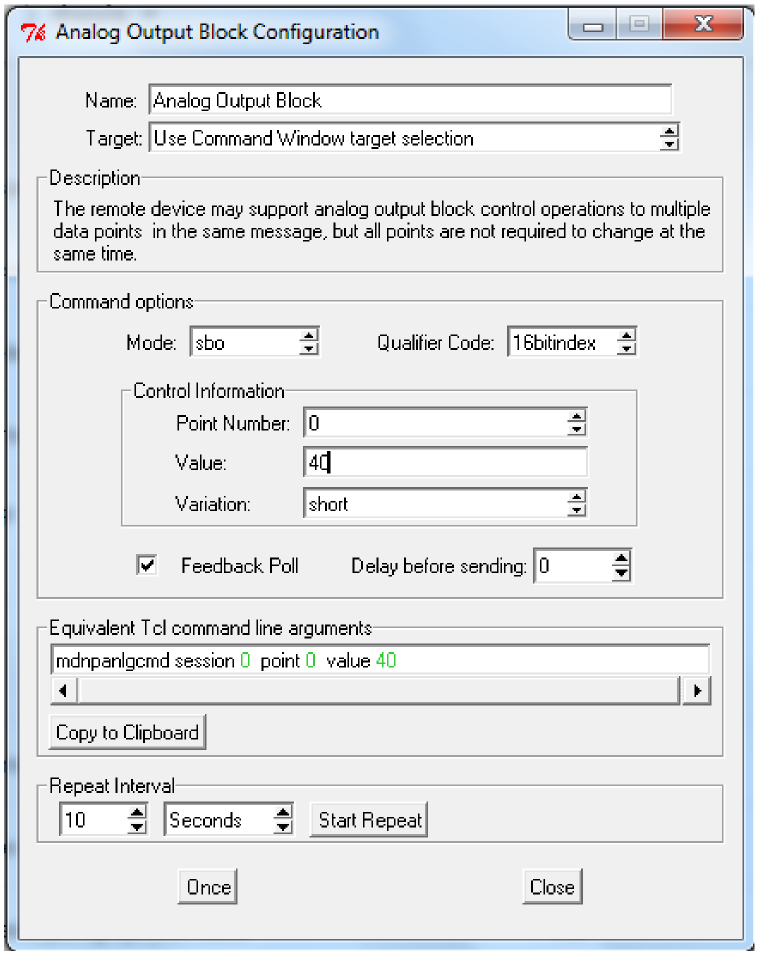


Figure 6. 4 Command window of analog output

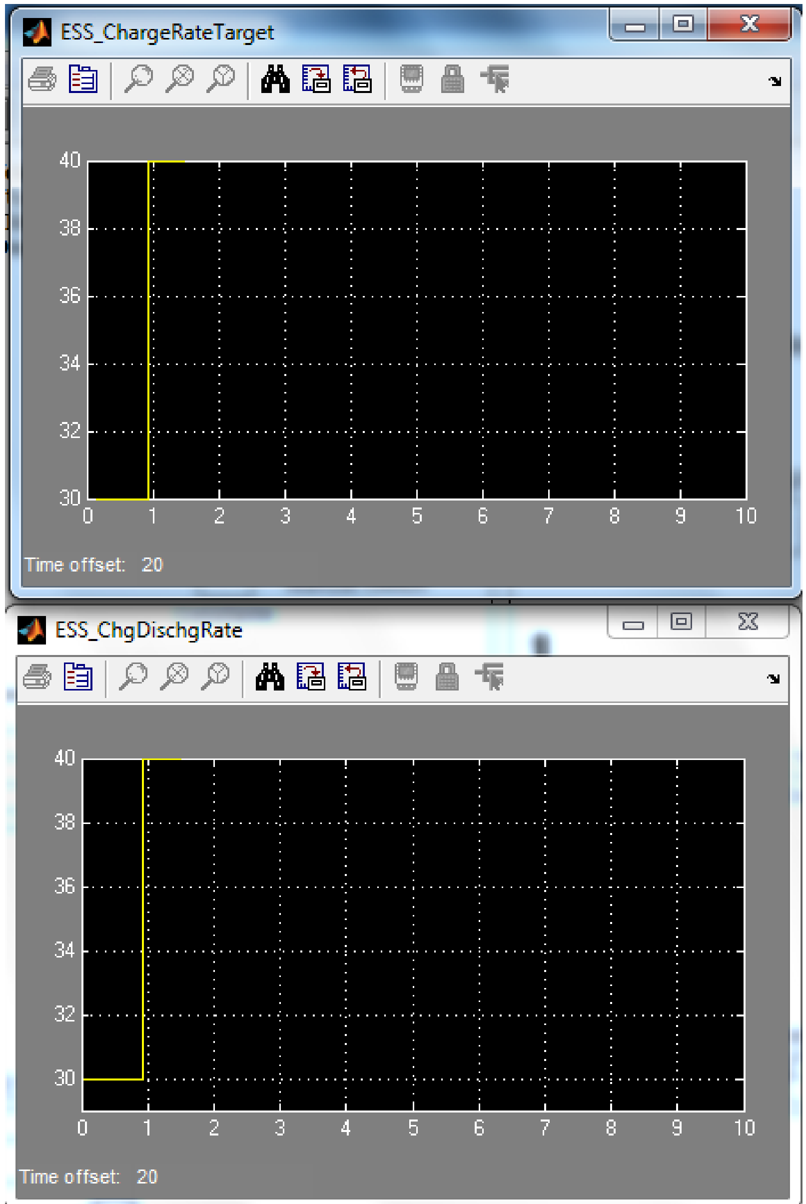


Figure 6. 5 ESS_ChargeRate Target and ESS_ChgDischgRate values

A similar method is used when testing the model's binary outputs response.

Initial values are shown in Figure 6.6. Comparing the actual initial values pre-defined in our model (in figure 6.7), it's easy to find out there's a gap between the configuration and results.

All three binary outputs should be 1 instead of 0 in Test Harness. This observation turns out to be a bug of "OpDNP3_AsyncSlaveCtrl" block in RT-LAB version 10.5, which is corrected in version 11.0, claimed by their technical support team. Yet by the time this test is conducted, RT-LAB 11.0 is not installed in the test platform. So the bug of initial values of binary output is recorded, and the ability of receiving binary output and executing the command is tested in this thesis.

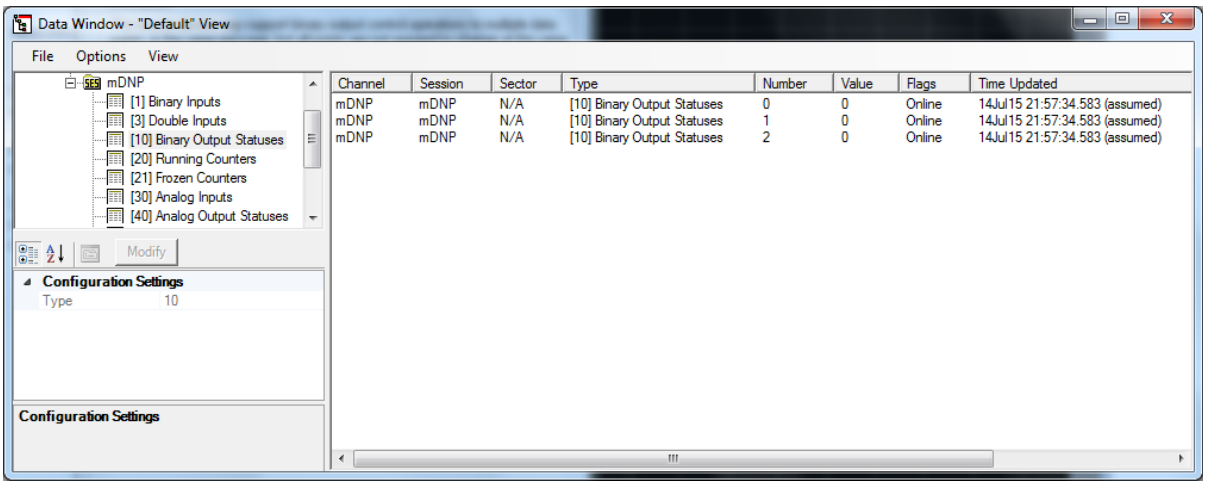


Figure 6. 6 Binary output initial values

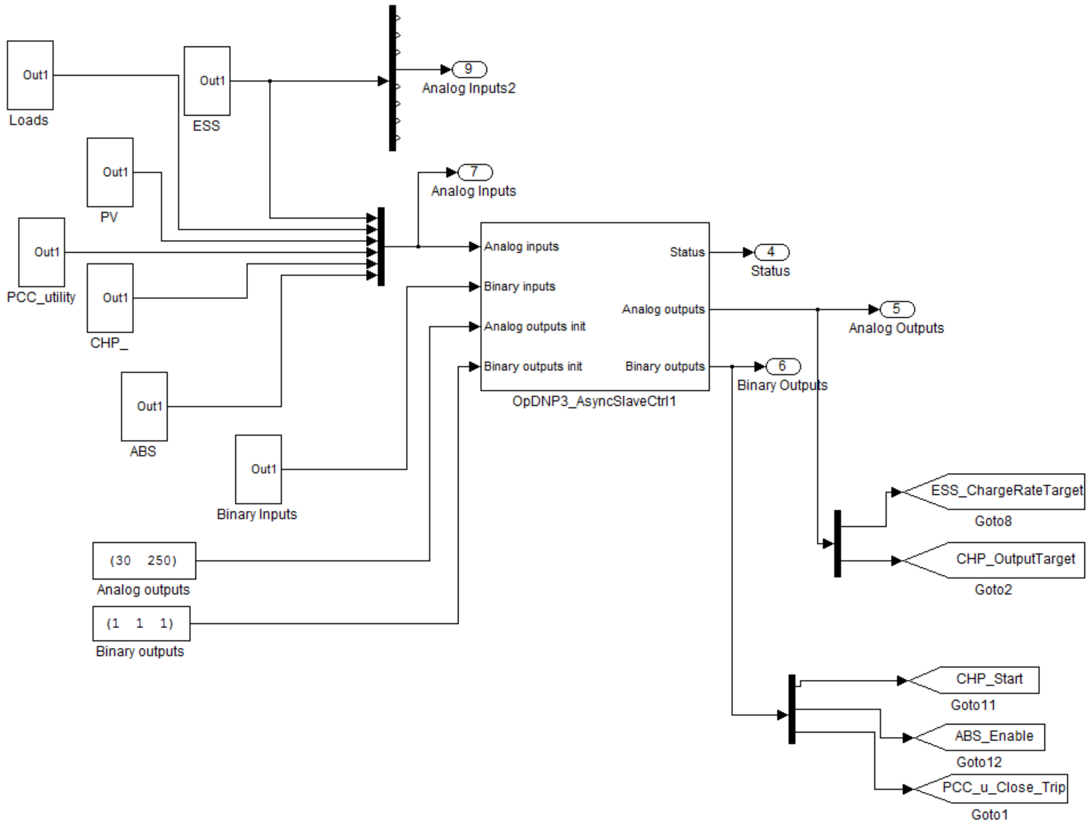


Figure 6. 7 DNP3 points configuration in outstation

The binary output point "CHP_Start" is chosen in order to examine the binary output capability. By launching this start command, the output of the CHP unit should increase from 0 immediately. So "CHP_kW_tot", which stands for the real power output of CHP unit, is chosen to be an indicator of the CHP status, off or on. As is shown in figure 6.8, a CHP start command—binary output with value 1 and index 1—is sent to the model.

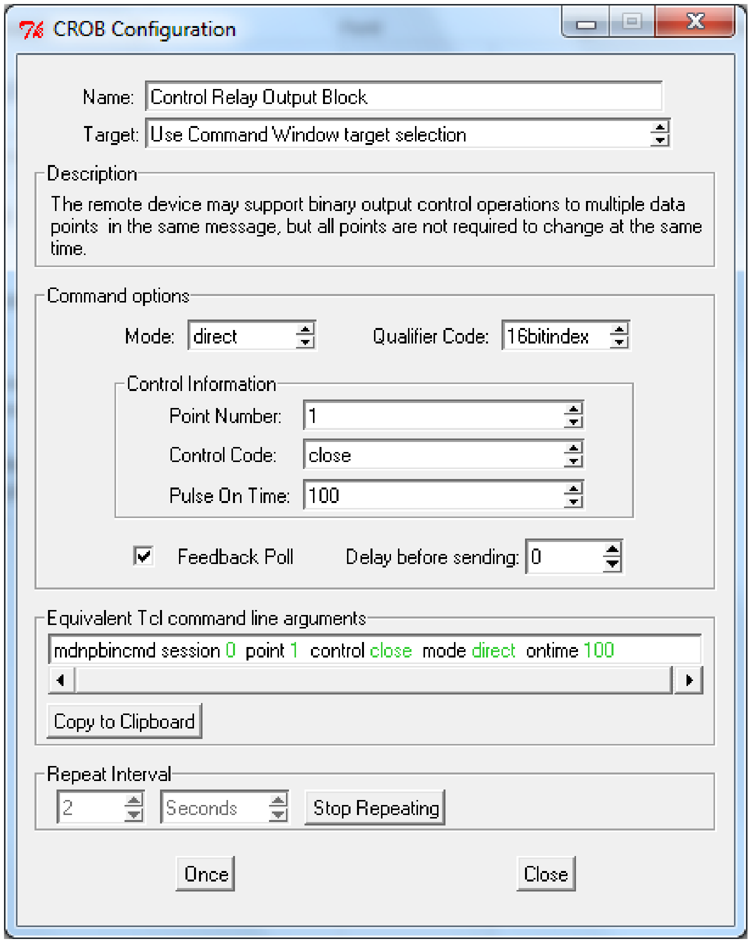


Figure 6. 8 Command window of binary output

It can readily be see that the command "start" is received and executed, which can be justified since the output increases as soon as the value of the binary output point turn to 1. So it can be concluded that the model supports binary output, even though it contains a bug in RT-LAB 10.5 version of binary output initial value configuration.

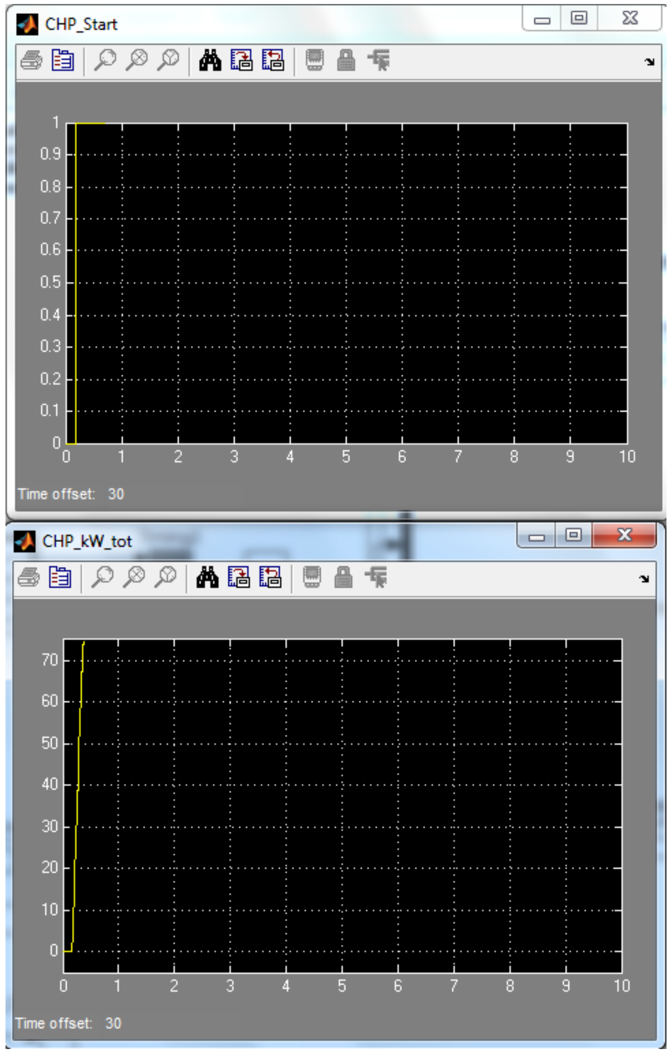


Figure 6. 9 CHP_Start and CHP_kW_tot value change

Analog input capability is examined by polling and checking the response in Test Harness visually. From Figure 6.10 we can see that all points are updated at the same time, when the integrity poll is launched. Figure 6.11 shows the result of binary inputs of the same poll command.

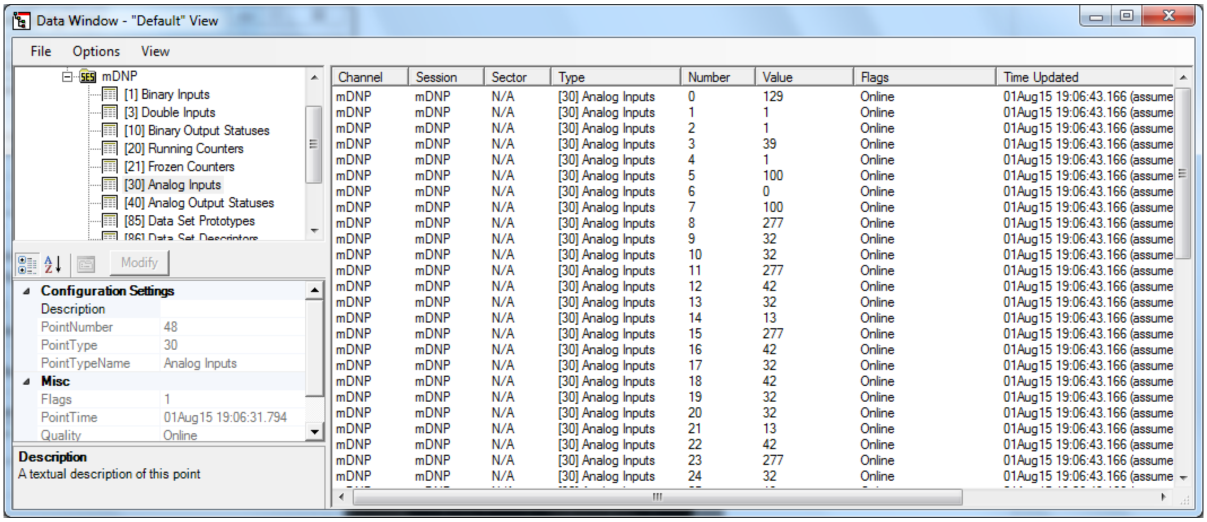


Figure 6. 10 Poll for analog inputs

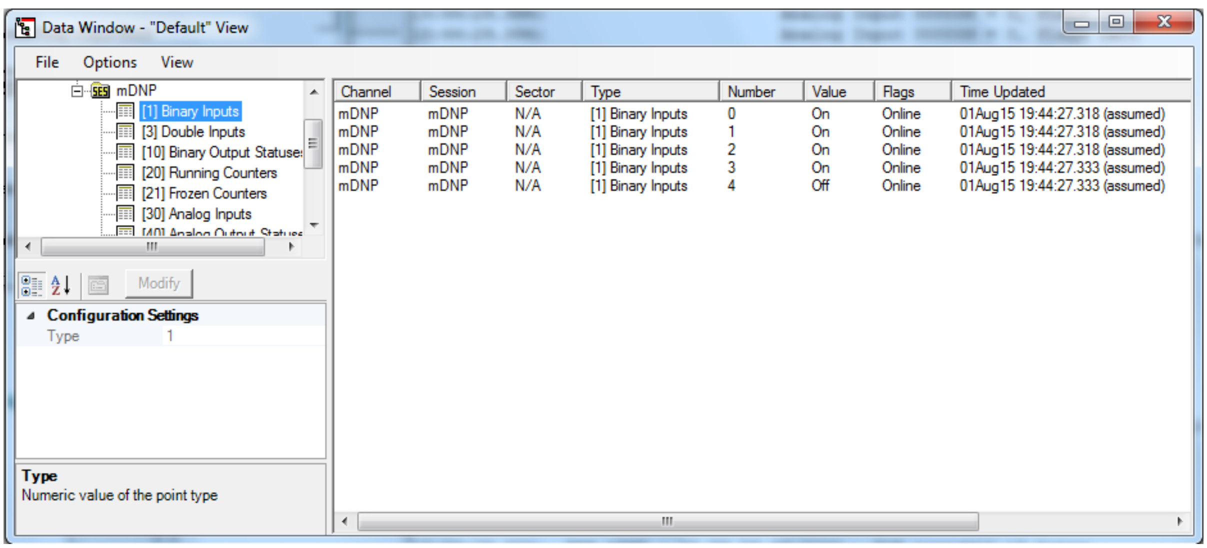


Figure 6. 11 Poll for binary inputs

From the tests and results listed above, full data exchange capability over DNP3 is verified in the microgrid model.

6.2.2 Time Synchronization

Time synchronization capability is supported by the DNP3 interface in the microgrid model. By sending time synchronization commands through command window in Test Harness, we can see the binary inputs sent back with time stamps.

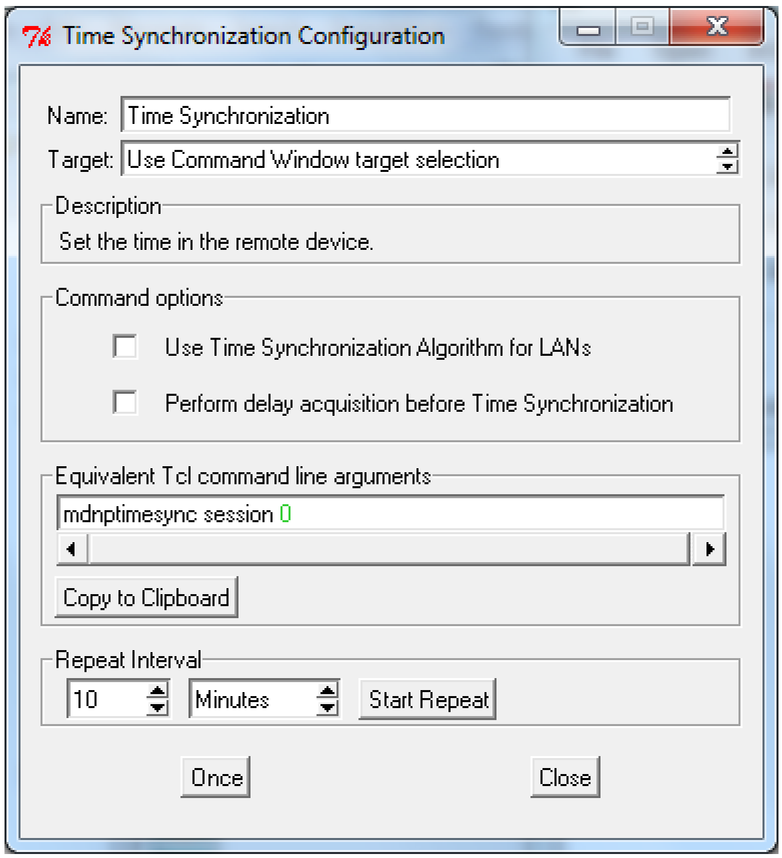


Figure 6. 12 Time Synchronization command window

Unlike the integrity poll, we don't need to send repeat commands in order to see inputs with stamps continuously.

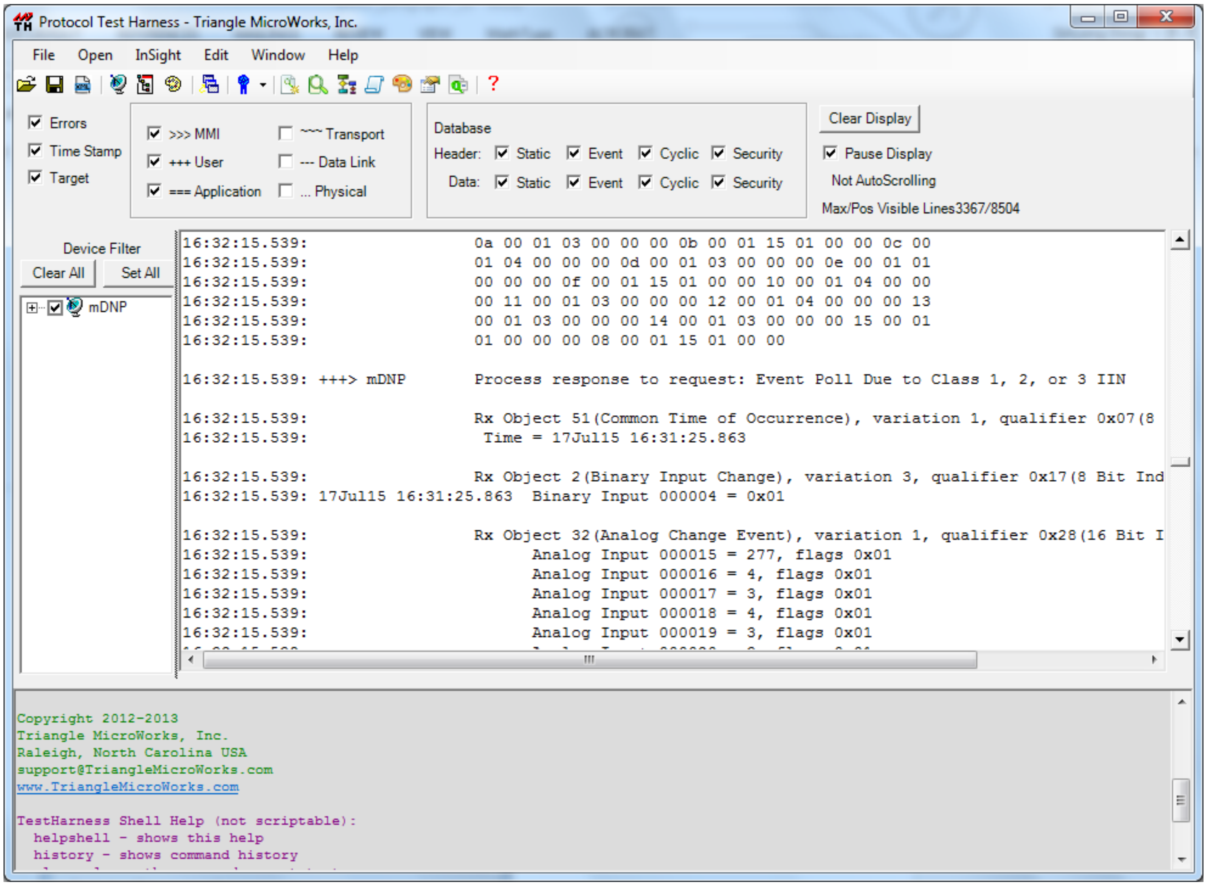


Figure 6. 13 Binary Input Change with time stamp

Whether the data contains a time stamp or not is also subject to DNP3 object variation. Object 2, variation 3, also referred to as Binary Input Change with time stamp, is generated and reported when there's a change of binary input points. Yet Object 32, variation 1, which refers to Analog Change Event without time stamp, does not contain any time stamps. These variation types are pre-defined in DNP3 functionalities in RT-LAB. So after time is synchronized in the outstation, the only data type reported to the master station with time stamp is binary input change.

6.2.3 Enable Unsolicited Message

Enable/ disable unsolicited message is also a one-click command using Test Harness. After enabling unsolicited message, the outstation sends data changes every 1 second without master station polling. Results are shown in Figure 6.15.

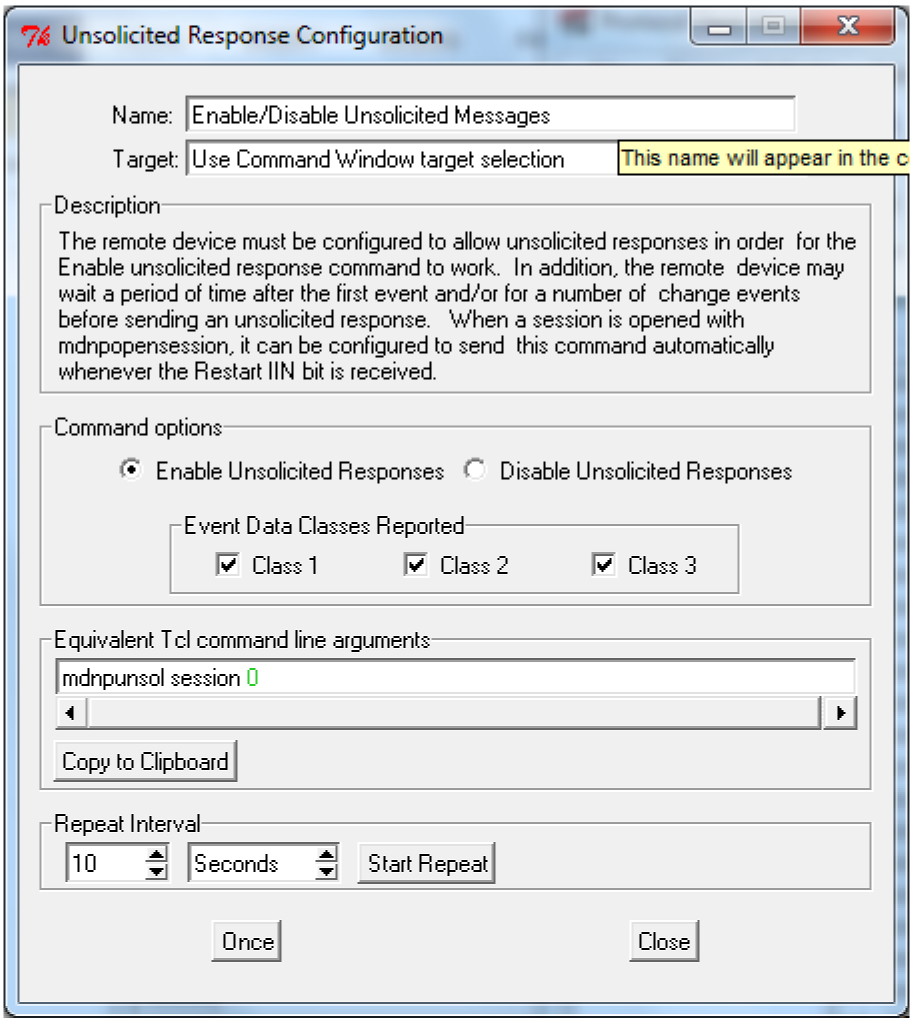


Figure 6. 14 Enable/Disable Unsolicited Messages commands window

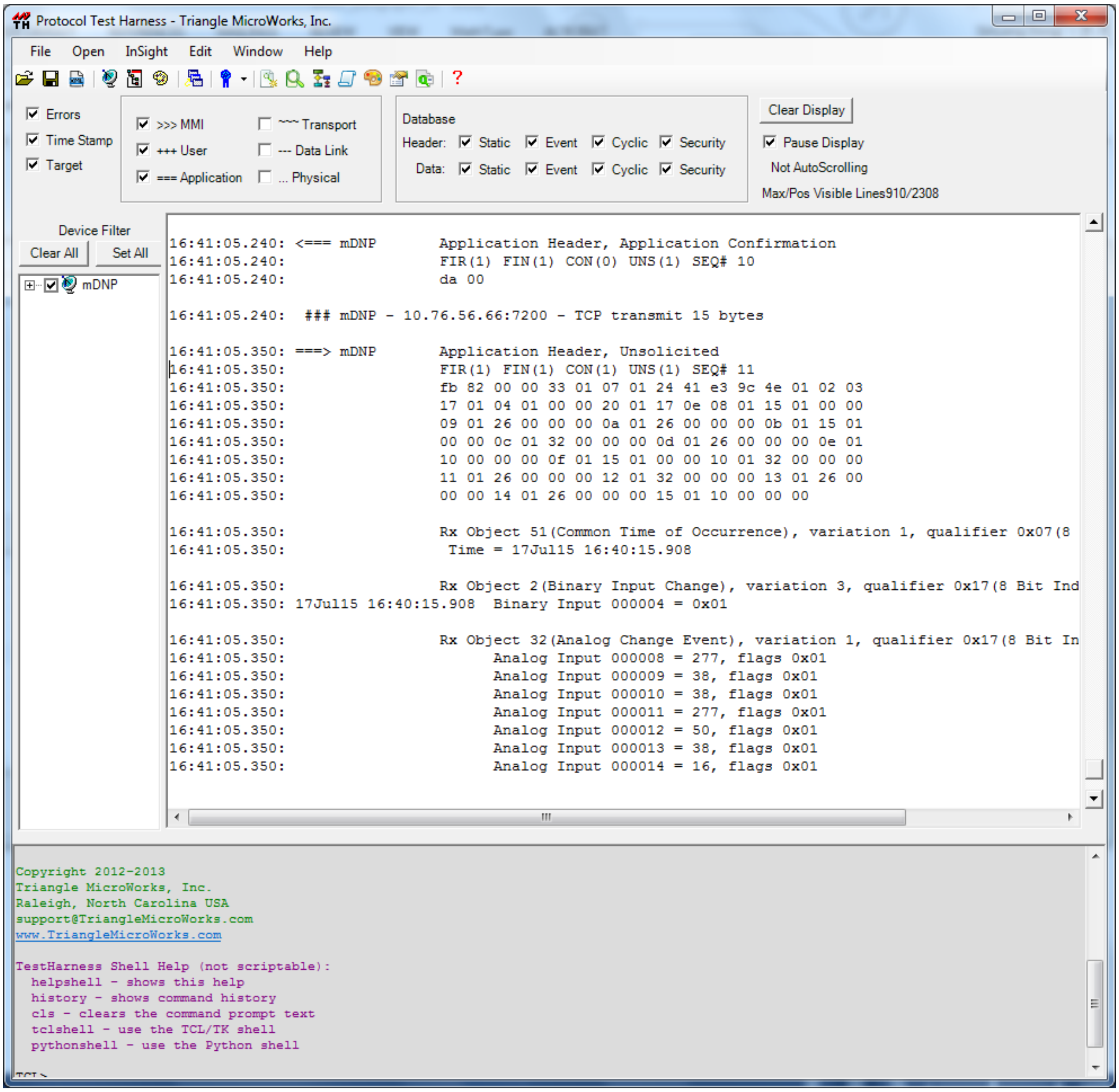


Figure 6. 15 Unsolicited messages sent by outstation

Data exchange functionalities including response to polling, receiving outputs and executing commands are tested and validated in this chapter. The abilities to support time synchronization and unsolicited message are also examined. Thus the conclusion that the microgrid model in RT-LAB supports basic DNP3 communication capabilities can be drawn.

6.3 LabVIEW DNP3 Interface Test

The prototype DNP3 master station interface described in Chapter III is tested here to make sure it has basic data exchange capability. The test examined four data types: analog input, binary input, analog output (setpoint) and binary output (control). The component used in this test is the Energy Storage Unit (ESS). An extra control point “ESS_Enable” is added for test purpose.

The analog point with index 0 is the ESS capacity, which is a constant with value 129 (kW). The analog point with index 3 is ESS real power output, “ESS_ChgDischgRate”, which should follow the value of setpoint “ESS_ChargeRate Target”. The point “ESS_ChgDischgRate” also indicates if the unit is enabled or not. The binary output point “ESS_Enable” has an index of 3 and default value of 0, which means the Energy Storage Unit is disabled by default. The first step in this test is to set this point to 1, which enables the unit.

Figure 6. 16 Energy Storage Unit enabled

Figure 6.16 above shows the analog input with index 3 has experienced a change from 0 to 40 in enabling the unit. Thus the binary output works in DNP3 communication. Then the second step is to examine setpoint “ESS_ChargeRate Target” with index 0. The original value for this point is 40, shown in Figure 6.16. In this step we change the value into 30, and click on the “Execute2” button.

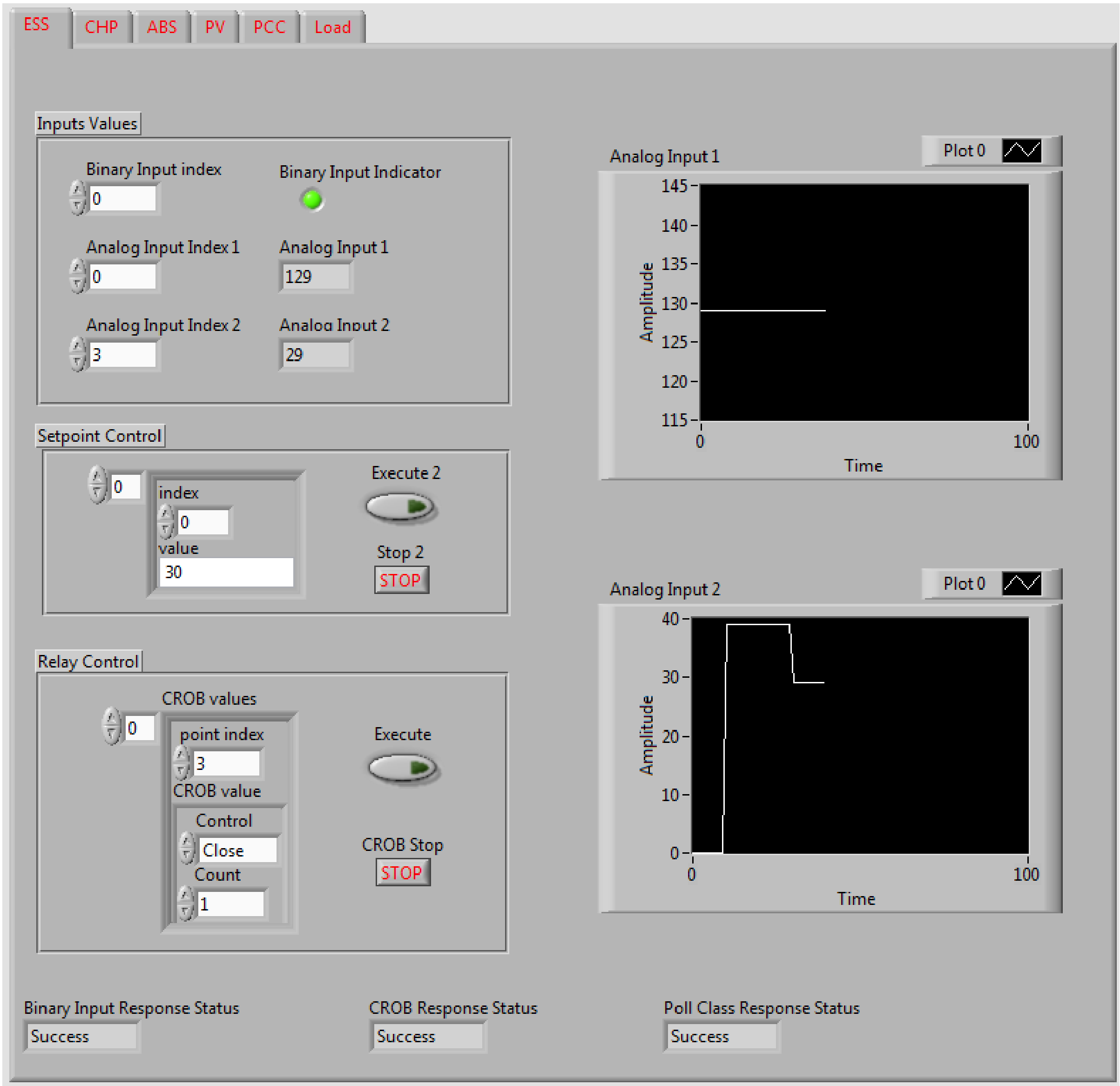


Figure 6. 17 Setpoint change in ESS unit

The analog input 2 chart in Figure 6.17 clearly shows a change of the real power output of ESS unit. Thus we can say the analog output data type is supported by LabVIEW.

By changing the binary input index, the capability of correctly receiving binary inputs is examined. The binary input with index 3 is 1 (or ON) and the other binary input with index 4 is 0 (or OFF). These values are the same with the system setting, thus the binary input data type is also supported by LabVIEW.

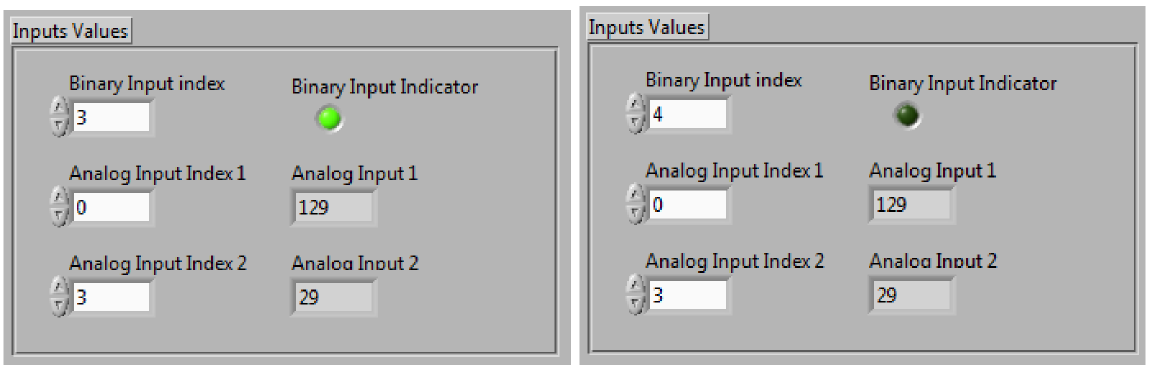


Figure 6. 18 Binary inputs values in LabVIEW

Analog input examination is included when testing analog output points, so a conclusion can be drawn that the LabVIEW master station properly supports all four basic data types within DNP3 protocol.

Chapter VII. Conclusions and Future Work

The thesis work focuses on implementing DNP3 protocol into a microgrid testbed and testbed validation. The first 2 chapters provide background information about microgrids, and the Olney Town Microgrid project which the thesis is part of. The third chapter introduces DNP3 protocol and a method of implementing it into the testbed. Chapter Four explains what simulation validation is and why it is needed. Several test plans are given for future reference. Chapter Five and Six focus on tests and their results, including single model tests and communication tests.

The Olney Town Microgrid project is still a work in process. Though a lot of effort was put into supporting the communication and validation parts in doing the thesis, there is still a lot work to be done.

A DNP3 master interface based on LabVIEW platform is introduced in Chapter Three and tested in Chapter Six, though there's still opportunity to further enhance its performance. Functionalities like file reading and automated commands sending should be explored when automating test process using LabVIEW. Theoretically this platform is also capable of recording data, further processing data and creating a more user-friendly Human Machine Interface. These are options should be considered in future development within.

In Chapter Four, several test plans are developed based on corresponding use cases. These test plans are based on a design of hardware-in-the-loop test setup, in which a SEL 451 relay might be included. In that case, the test plans can be helpful. At this time a new OPAL hardware system is being building up and not much detail is available. So the test plans aiming to further explore model capability in supporting microgrid controller use cases need to be considered and enhanced before commissioning.

The points list for the microgrid controller gives an idea of what kind of functionalities are expected in each model. In black start and island mode, frequency and voltage fluctuations are key factors. Thus dynamic analysis would be important in a system evaluation for these situations. Certain models do need dynamic characteristics to support the points list and microgrid controller commands. At this time, the FREEDM testbed Zone 1 is focused on representing static features of the models and is lacking dynamic features. Models with dynamic features are being developed, and will be included in the testbed to evaluate system dynamics in the near future.

REFERENCES

[1] Schwaegerl, Christine, and Liang Tao. "The Microgrids Concept." *Microgrids: Architectures and Control (ed N. Hatziargyriou), John Wiley and Sons Ltd, Chichester, United Kingdom. doi* 10 (2013): 9781118720677.

[2] Zadeh, M. R. D., et al. "Design and implementation of a microgrid controller."*Protective Relay Engineers, 2011 64th Annual Conference for*. IEEE, 2011.

[3] Kosterev D, Meklin A. Load Modeling in WECC[C]. IEEE Power System Conference And Exposition, 2006.

[4] www.energy.gov

[5] "The World Market for Substation Automation and Integration Programs in Electric Utilities: 2005-2007," Newton-Evans Research, September 2005.

[6] http://www.trianglemicroworks.com/

[7] Ktiraei, F., et al. "Microgrids management-controls and operation aspects of microgrids." *IEEE Power Energy* 6.3 (2008): 54-65.

[8] Dufour, Christian, Cacilda Andrade, and Jean Bélanger. "Real-Time simulation technologies in education: A link to modern engineering methods and practices." *Proceedings of the 11th International Conference on Engineering and Technology Education,(INTERTECH-2010), Ilhéus, Bahia, Brazil*. 2010.

[9] Lundstrom, Blake, et al. "An Advanced Platform for Development and Evaluation of Grid Interconnection Systems Using Hardware-in-the-Loop: Part III--Grid Interconnection System Evaluator." *Green Technologies Conference, 2013 IEEE*. IEEE, 2013.

[10] None, None. *BORREGO SPRINGS MICROGRID DEMONSTRATION PROJECT*. San Diego Gas & Electric Company, 2013.

[11] https://building-microgrid.lbl.gov/

[12] Hirose, Keiichi, J. T. Reilly, and H. Irie. "The sendai microgrid operational experience in the aftermath of the tohoku earthquake: a case study." *New Energy and Industrial Technology Development Organization* 308 (2013).

[13] Balci, Osman. "Principles and techniques of simulation validation, verification, and testing." *Simulation Conference Proceedings, 1995. Winter*. IEEE, 1995.

[14] Dong, Han, He Renmu, and Ma Jin. "Power system dynamic simulation validation based on similarity theory and analytical hierarchy process." *Power System Technology, 2006. PowerCon 2006. International Conference on*. IEEE, 2006.

[15] Rehman, Muniza, and Stig Andur Pedersen. "Validation of simulation models."*Journal of Experimental & Theoretical Artificial Intelligence* 24.3 (2012): 351-363.

[16] Knepell, Peter L., and Deborah C. Arangno. *Simulation validation: a confidence assessment methodology*. Vol. 15. John Wiley & Sons, 1993.

[17] Guttromson, Ross, and Steve Glover. "The advanced micro-grid integration and interoperability." *Sandia National Laboratories, Sandia report* (2014).

[18] EERE, DOE. "Summary Report: 2012 DOE Microgrid Workshop." *Chicago, Illinois, Jul* (2012).

[19] www.forbe.com

[20] Standards Coordinating Committee 21 on Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage. "IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems." (2011).

[21] www.greenenergycorp.com/

APPENDICES

Appendix A

This appendix contains all points in the microgrid model and their detailed information.

Load

Added?	Name	Type	Unit	Comment
Y	Amps	Analog Input	A	Current flow injected into loads.
Y	kVAR	Analog Input	kVAR	Reactive power consumed by loads.
Y	kW	Analog Input	kW	Active power consumed by loads.
Y	Volts	Analog Input	V	Load voltage.

PV

Added?	Name	Type	Unit	Comment
Y	kW_cap	Analog Input	kW	This is a constant value, referring to the capacity of PV.
Y	kW_tot	Analog Input	kW	This is the measured output power.
NF*	%_cap	Analog Input		Percentage the output of capacity.
Y	Status_Ena_Dis	Binary Input		

* Not needed in FREEDM testbed.

ESS

Added?	Name	Type	Unit	Comment
Y	Capacity kWh	Analog Input	kWh	This is a constant value, referring to the capacity of ESS unit.
Y	ChargeRateMax	Analog	kW	It’s a pre-defined Constant.

		Input		Name plate value is needed.
Y	DischgRateMax	Analog Input	kW	It's a pre-defined Constant. Name plate value is needed.
Y	ChgDischgRate	Analog Input	kW	Actual charge or discharge rate. Positive value means a charge rate, negative value means a discharge rate.
Y	Efficiency	Analog Input		It's a pre-defined Constant. Name plate value is needed.
Y	SOC	Analog Input	%	Charge State of the battery, 100% means full, 0% means empty.
Y	SOC_Max	Analog Input	%	SOC_Max is associated with depth of discharge, should be given as the parameters of ESS. In GEC website, they use 100% as the max value.
Y	SOC_Min	Analog Input	%	SOC_Min is associated with depth of discharge, should be given as the parameters of ESS. In GEC website, they use 0% as the min value.
Y	ChargeRateTarget	Analog Output	kW	Targeted charge rate. Positive value means a charge rate, negative value means a discharge rate.
N	Mode	Analog Output		• Constant power • Ramp rate control: smoothing • Peak power management Is this command one of three numbers, and each number stands for one mode? • Grid forming

NG_CHP

Added ?	Name	Type	Unit	Comment
Y	Capacity	Analog Input	kW	This is a constant value, referring to the capacity of CHP unit.
Y	ElectricalOutputRealPower	Analog Input	kW	This is the measured output real power.
Y	ElectricalOutputReactivePower	Analog Input	kW	This is the measured output reactive power.
N	ElectricalOutputFrequency	Analog Input	Hz	This is the measured output frequency.
Y	ElectricalOutputCurrent	Analog Input	A	This is the measured output current.
Y	ElectricalOutputVoltage	Analog Input	V	This is the measured output voltage.
Y	RecoveryInletTemp	Analog Input	Fahrenheit	Exhaust temperature.
Y	InletAirTemp	Analog Input	Fahrenheit	Ambient temperature.
Y	BTUoutput	Analog Input	Btu_hr	
N	Readiness	Binary Input		It means the device is applicable in blackstart or in other words, the CHP unit is ready. The principle to decide readiness status is needed.
N	Status Start/Stop	Binary Input		Indicator of CHP status.

Y	OutputTarget	Analog Output	kW	This is the setpoint of power output for CHP unit.
N	SetPowerFactor	Analog Output		Set desired power factor for CHP output.
N	SetMode	Analog Output		• regular generator • Master device (modulating frequency and voltage)
Y	Start	Binary Output		Start CHP unit.
N	Stop	Binary Output		Stop CHP unit.

ABS

Added?	**Name**	**Type**	**Unit**	**Comment**
Y	Ent_Tmp	Analog Input	Fahrenheit	Temperature of entering exhaust.
N	Status_Ena_Dis	Binary Input		Indicating the unit is enabled or disabled.
N	Status_Heat_Cool	Binary Input		Indicating which mode the absorption chiller is in, heat or cool.
N	Heat	Binary Output		Enable heating mode.
N	Cool	Binary Output		Enable cooling mode.

In FREEDM testbed zone 1, there are ten loads, three PV units, one CHP, one ESS and one ABS. Among the points listed in Appendix A, 55 analog inputs, 5 binary inputs, 2 analog outputs and 3 binary inputs are implemented.

Appendix B

This appendix contains several test plans which are designed according to specific microgrid controller use cases. Assuming a SEL relay is added in testbed, these test plans are designed to be conducted in a Hardware-in-the-Loop environment.

Test plan for user case #F-5: Islanding to Grid-Connected Transition Test

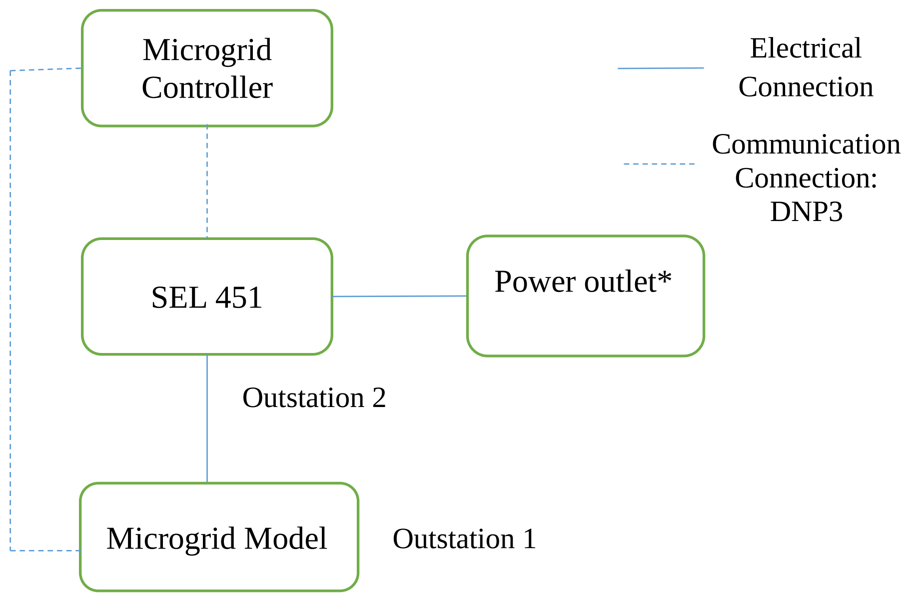
1. Description

A microgrid should be capable of resynchronizing and reconnecting to the APS to transition from islanded operation mode to grid-connected operation mode. The complete resynchronization and reconnection process is described in the following step-by-step table.

2. Scenarios

There is only one scenario in this test. The microgrid is operating in normal islanded mode, and the AEPS (Area Electric Power System) is also in normal operation mode. The microgrid controller is capable of communicating with AEPS to make sure get operation status and get permission to reconnect.

3. System Setup



*Power outlet is used to represent AEPS in the test.

4. Test Procedure

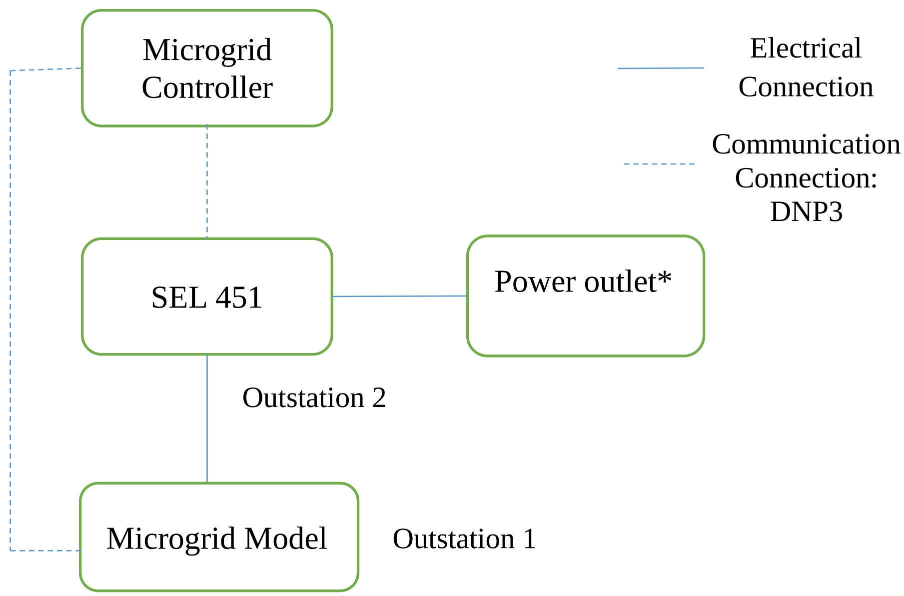
Step	Action	Need confirmation from outstation? (Y/N)
1	Poll for microgrid operating status and AEPS status. Making sure they are both in normal condition.	Y
2	Send and execute resynchronization dispatch commands to microgrid models.	Y
3	Close SEL 451.	Y
4	Initiate grid-connected mode to primary source.	Y
5	Check if the microgrid model is operating normally.	Y

Test plan for user case #F-6: Energy Management Test

1. Scenarios

A microgrid has two operation modes, Grid-connected mode and Islanding mode. The operation conditions, system constraints, and operation objectives could be different in different modes. In Grid-connected mode, the microgrid Energy Management System (EMS) communicates with the distribution system, manages the microgrid to comply with the utility policies and regulations, makes operation decisions based on the internal conditions as well as the utility requirements, and provides ancillary services under the distribution system's commands. In islanding mode, the primary objectives of the microgrid EMS are to maintain the stability, to regulate the voltage and frequency within certain ranges, and to optimize the microgrid overall performances.

2. System Setup



3. Test Procedure

This test will currently focus on effectiveness of microgrid model in supporting the microgrid controller energy management functionality. Thus the model needs reliable communication to receive commands and report status, as well as efficiently execute the commands received. Thus the design of this test will stress on two parts: 1) reliable DNP3 communication for responding to master poll and receiving commands; 2) effectively react to commands, especially commands with different set points or modes. And the two features of the model would ensure controller operate properly in both grid-connected mode and islanded mode.

In order to make sure the model has proper DNP3 interface to microgrid controller, we design and develop a DNP3 master to represent the communication interface of real controller. DNP3 communication between microgrid model (DNP3 slave) and DNP3 master are mainly exchange of information, which can be classified into two categories: Inputs and outputs. Inputs are information - either binary or analog - feed to DNP3 master, representing model status on different components;   Outputs are commonly referred to as commands, can be either binary outputs or analog outputs.

The DNP3 master is designed to be capable of sending outputs to model, polling status data and showing the data in real time on a Human Machine Interface. It contains basic functionalities of DNP3 data exchange. Complex capabilities written in User Cases are not supported, such as voltage and frequency control, energy management or economic dispatch. And procedures will be examining sending and receiving separately.

Step	Action	Need confirmation from outstation? (Y/N)
1	Build DNP3 communication by configuring correct setting parameters to model and DNP3 master.	Y
2	Check if two stations are connected by pinging model IP in command prompt window.	Y
3	Start polling for binary analog inputs.	
4	Check if inputs are same as shown in model for both constants and changing ones. A display of same inputs on model side is needed beforehand.	Y
5	If results of above procedures are positive, continue to next step. If not, debug and run step 1-4 again.	N
6	Check SEL 451 status. Send opposite command to the device and see if it operates correctly. If yes,	N

	continue to next step; if not, stop the test and check communication.	
7	Send analog outputs to model, and check display on model and DNP3 master. Send one different output at a time, and make sure output for every component in model is received and executed.	N
8	Send binary outputs to model, and check display on model and DNP3 master. Send one different output at a time, and make sure output for every component in model is received and executed correctly.	N
9	If results of above procedures are positive, stop running model and master and disconnect communication. If not, debug and run step 7 and 8 again.	N

Test plan for user case #F-7: Microgrid Protection Test

1. Description:

Point of Common Coupling (PCC) is the point defines microgrid edge to the whole grid. There are two PCCs in the microgrid, one is called head PCC and the other one is tail PCC. Breakers are implemented into these points and execute commands from the microgrid controller. The protection test focuses on if the breakers at PCCs trip in abnormal conditions, like voltage or frequency sag.

2. Scenarios:

a) Normal condition.

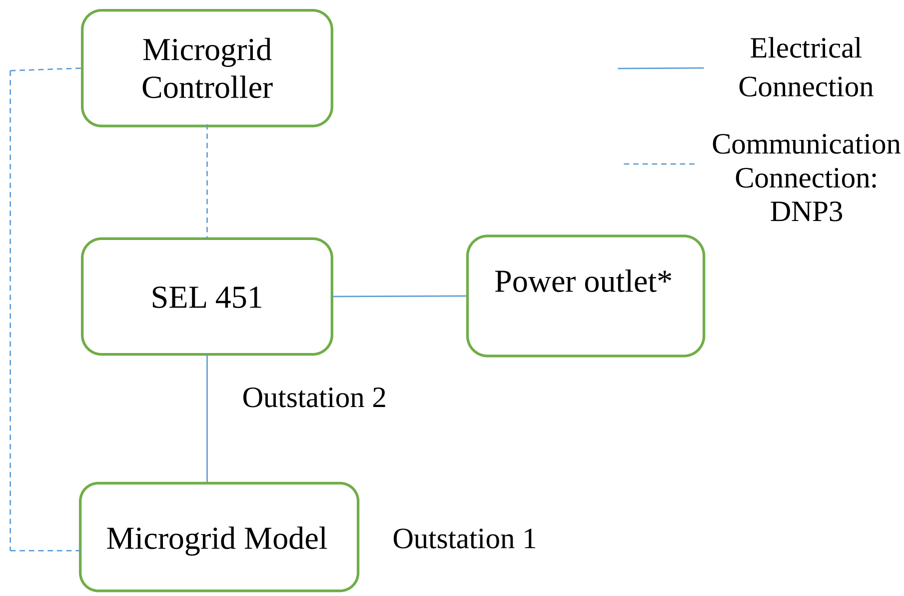
When the system is operating normally, the controller need to maintain the stable state by ensuring status of all circuit breakers unchanged. See if the relay automation control keeps the circuit breaker at PCC closed.

b) Fault condition.

If a fault occurs, protection devices detect the fault, and then tripping decisions are made and sent to circuit breakers or other fault current interruption devices. The decisions are sent either by a local protection device, or by a remote protection device which has communication with the local protection device.

After the tripping signals are executed, the microgrid status and topology may be changed. The new status is sent to the protection controller, and then to the microgrid SCADA. The microgrid status is sent to the area power system, either for monitoring purposes or for incorporation into real-time operations.

3. System setup



*Power outlet is used to represent AEPS in the test.

4. Test procedure

Step	Action	Need confirmation from outstation? (Y/N)
1	Decide the upper and lower threshold of voltage (or frequency) at PCC.	N
2	Make sure the thresholds are correctly stored in the Microgrid Controller, with proper automated trip/close logic settings.	N
3	Run the model in RT-LAB in real time, and connect master to the model and relay.	Y
4	Test one parameter at a time, say voltage higher than upper threshold, to see if the relay trips the breaker or not. If the relay act as expected (trip in	Y

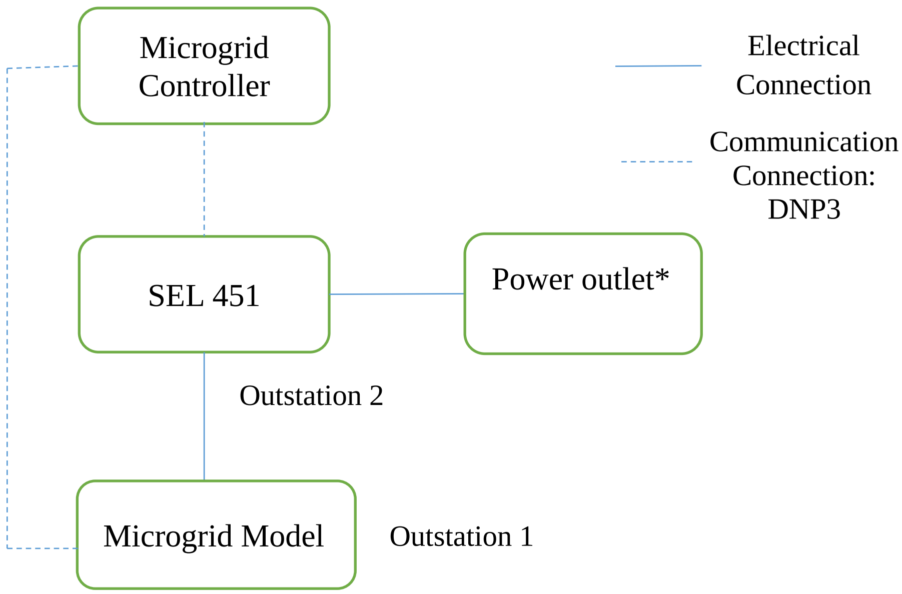
	this case), then close the breaker by remote control and move to another value.	
5	Choose another group of threshold and repeat procedures 2-4.	N

Test plan for user case #F-9: Microgrid Blackstart Test

1. Scenarios

Blackstart is discussed in detail in Chapter 4. The scenario in this test is the whole microgrid model stops running, all system components are shut down. The SEL relay device can be either open or closed, representing situations where the grid beyond PCC is operating normally or down.

2. System setup



*Power outlet is used to represent AEPS in the test.

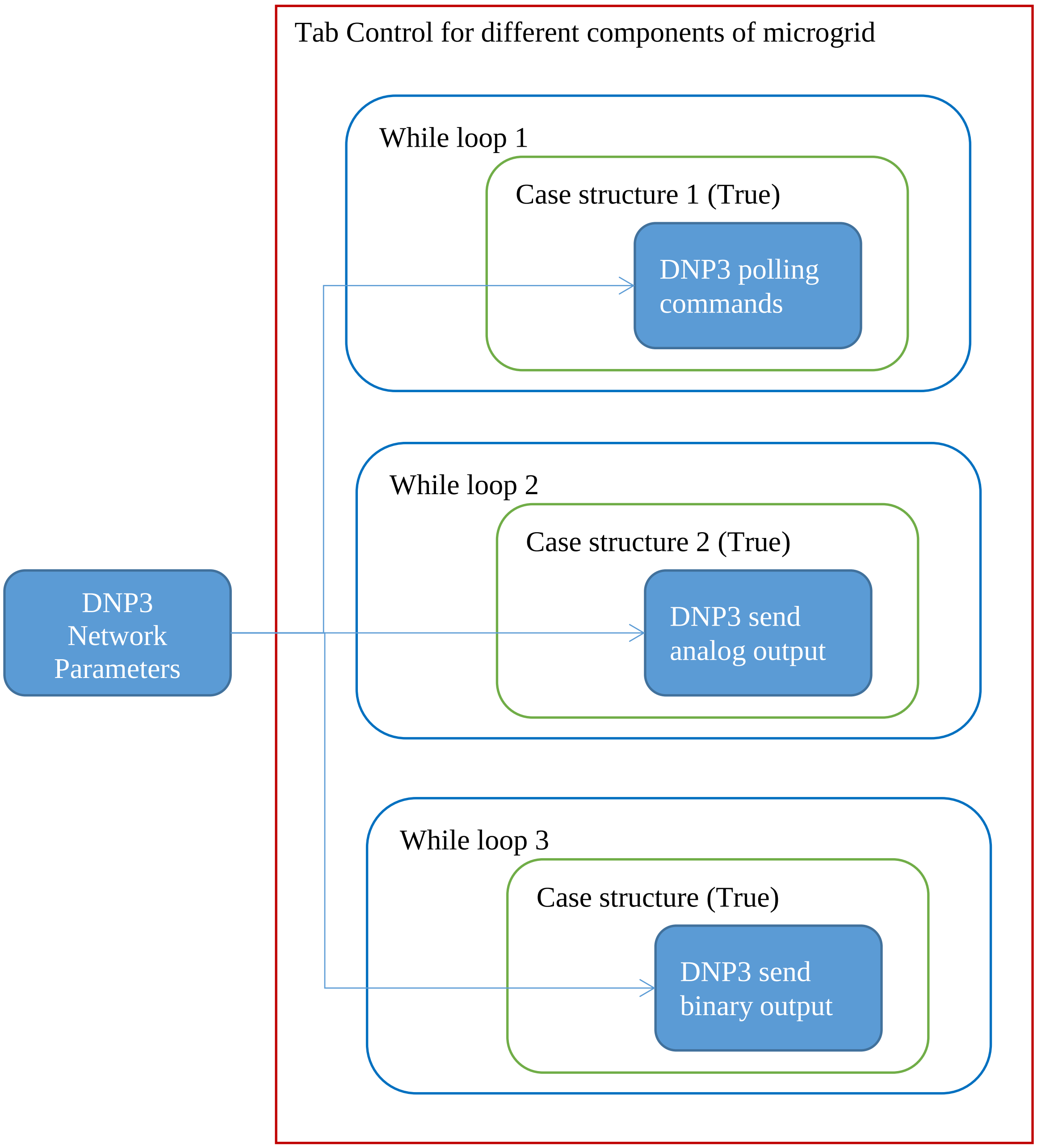
3. Test procedure

Step	Action	Need confirmation from outstations? (Y/N)
1	Poll for SEL 451 status and send open command.	Y
2	Open switchgears to isolate primary source and load with rest of the microgrid.	Y
3	Start primary source and match primary load. Poll for voltage and frequency.	Y
4	Follow pre-determined sequence to add other loads and sources.	Y
5	Islanded operation dispatch.	Y

6	Make sure the microgrid model is running in normal islanded condition by checking system operating data.	Y

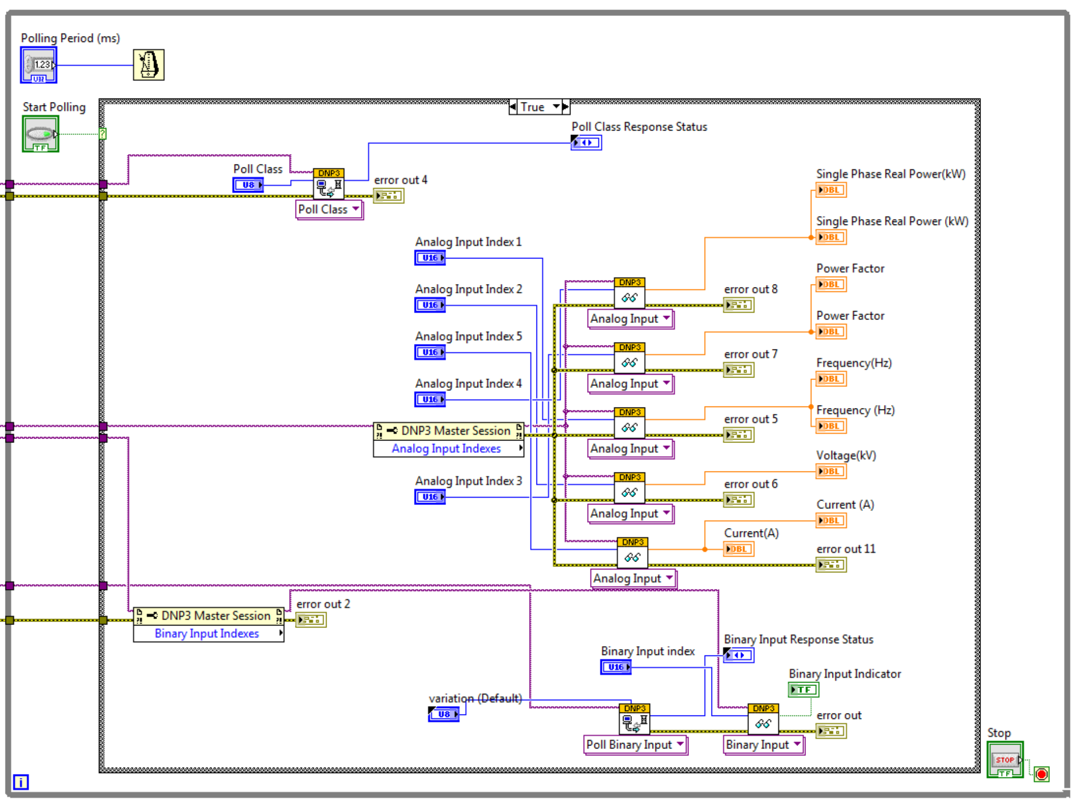
Appendix C

The whole block diagram program structure can be shown in figure below:



The reason to separate polling and other send outputs commands is for the user of the system to have counter control of sending setpoints and trip/close commands. Class data polling in LabVIEW is defaulted to be polling with a user defined time interval. So a while loop which will execute until stop button is triggered is suitable. Yet for output points, whether analog or binary, the system usually does not need to send the same user defined value to outstation continuously. Thus a while loop which scans the execute counters together with a case structure which stands for the command "send" is suitable in this situation. Execute button together with counter input of CROB (Control Relay Output Block) determines how many times the binary output value will be sent to outstation.

This is the block diagram for while loop 1, which is the polling part program.



The figure below shows the while loop 2 and 3, which are analog output and binary output sending scheme.