ABSTRACT

LONG, QIAN. Test Protocols for Evaluating Commercial Microgrid Controller. (Under the direction of Dr. David Lubkeman).

This research focuses on microgrid testbed development and test protocols design for evaluating the performance of commercial microgrid controller. The microgrid testbed is built based on a real-world distribution circuit and the modeling/validation techniques for distributed energy resources are briefly discussed in the thesis. Then in order to demonstrate the validation of the functionality of microgrid controller, a comprehensive set of test protocols are designed to define testing procedures, and evaluation methodology is proposed to show the performance of microgrid controller in supporting emission reduction, reliability enhancement and efficiency improvement of the grid. The test environment is implemented to support controller integration, test execution and automation, and post processing analysis. Also, a fully functional LabVIEW testing master is designed as an alternative master in case that the controller is offline. It is applied in the simulation to generate our own control pattern in order to do evaluation analysis on the use case Energy Dispatch – Grid Connected. The test results show that the developed microgrid testbed and test protocols are effective in performance evaluation of microgrid controller.

Test Protocols for Evaluating Commercial Microgrid Controller

by
Qian Long

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APPROVED BY:

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Dr. Srdjan Lukic Dr. Ning Lu

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Dr. David Lubkeman
Committee Chair

DEDICATION

To my parents and grandparents for their unconditional love.

To my teachers for their precious life lessons.

To all my friends for their care and support.

BIOGRAPHY

Qian Long was born in Jianli, China. He received his Bachelor of Science degree in Electrical Engineering and Automation from China Agricultural University in June 2014. He started to pursue a Master of Science degree in Electrical Engineering in North Carolina State University in August, 2014. His research interests include distribution system analysis, Volt/VAR control and microgrids.

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LIST OF ABBREVIATIONS

BESS	Battery Energy Storage System
CERTS	Consortium for Electric Reliability Technology Solutions
CHP	Combined Heat and Power
DER	Distributed Energy Resources
DG	Distributed Generation
DNP3	Distributed Network Protocol
DOE	U.S. Department of Energy
DR	Demand Response
DSM	Demand Side Management
ESP	Energy Service Provider
GHG	Greenhouse Gas
MMC	Microgrid Master Controller
PCC	Point of Common Coupling
SAIDI	System Average Interruption Duration Index
SOC	State of Charge

Chapter I. Introduction

1.1 The Microgrid Concept

Distribution grids are experiencing an evolution, often noted as Smart Grid. A smart grid generally refers to an electricity network that employs a class of innovative technology, including intelligent monitoring, control, and communication, in order to offer more reliable, resilient, affordable and sustainable electric services. Increasing integration of renewable energy resources, aging infrastructure of electrical systems, extreme weather events, and system security and resiliency needs. Those are all leading to these significant changes in how electricity is generated, distributed, managed and consumed. The availability of smart grids is critical to social, economic and environmental benefits [1, 2].

Microgrids, also characterized as the "building blocks of smart grids", are perhaps the most promising, novel network structure [2]. The key feature that distinguishes microgrids from any other type of distribution network structure is its control capabilities over local distribution network operation through DERs, such as energy storage devices, PV arrays, wind turbines, controllable loads and distributed generators. Generally, these control capabilities allow microgrids to be managed in an optimally economical and sustainable manner, interconnected to the main grid. However, due to grid faults or other interruptions, the microgrids can also be transitioned via appropriate control strategies into islanded operation mode, thus enhancing the resiliency of electric services. Since consequences of adverse weather, like hurricanes and ice storms, have driven a desire to make the power system more resilient, the microgrid technology has been drawing more and more attention in recent years [3].

Up to now, there is no agreement on the architecture of microgrids, or on how large or small microgrids should be with respect to energy capacity and geographic area. But there's one common feature: The microgrid should be able to isolate from the main grid and independently manage generation assets and balance the critical electric loads within the microgrid. The key components that enable this feature are: the circuit breakers that isolate the microgrid at the PCC or multiple PCCs, the microgrid controller that operates the system and maintains system stability and DERs. In the thesis, a definition of a microgrid from U.S. Department of Energy Microgrid Exchange Group is used:

> *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.*

A typical schematic of a microgrid system is shown as Figure 1.1. It is a community area served by one or more distribution substations and also supported by high penetrations of local DERs such as energy storage systems, micro-turbines, fuel cells and DR. Microgrid systems heavily rely on microgrid control center to provide monitoring, communication and control capabilities across the area in order to achieve a more sustainable, reliable, and economical electric energy system operation.

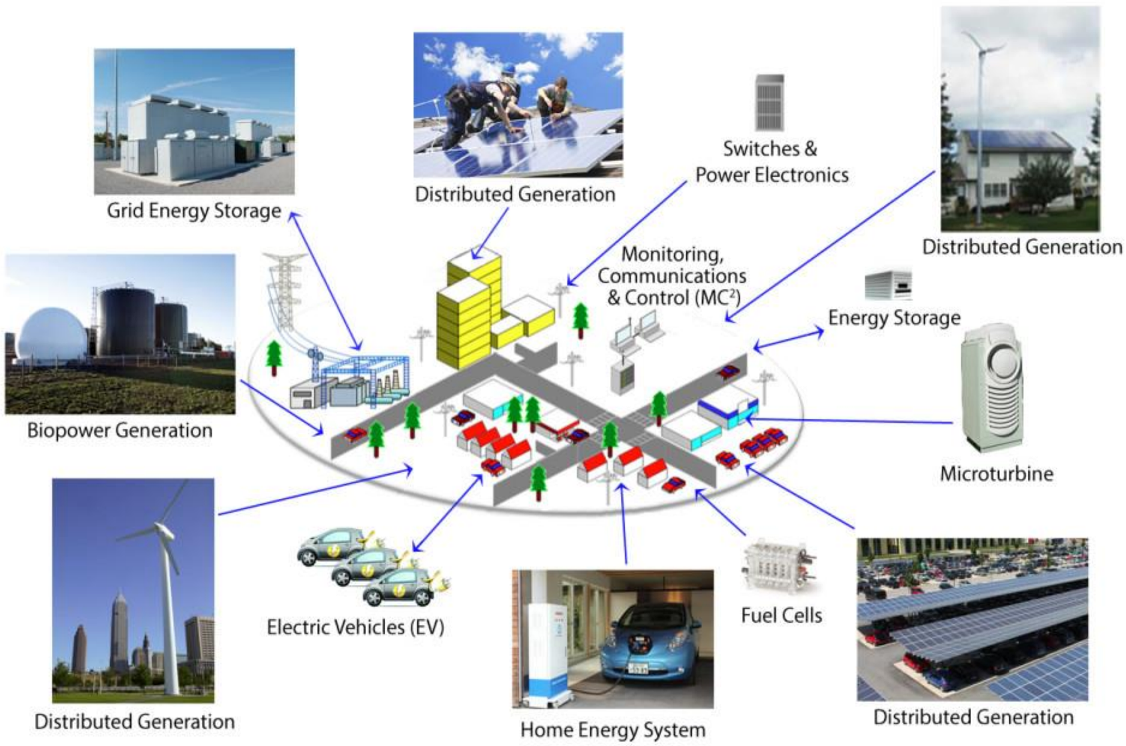


Figure 1.1 A typical microgrid schematic [4]

1.1.1 Overview of Potential Microgrid Impacts [2]

A microgrid can offer a large variety of economic, technical, environmental and social benefits to consumers, microgrid owners and utility:

Economic – In the microgrid framework, the internal energy market can potentially offer a lower price than retail level to customers and a higher price than wholesale level to microsource owners; from utility perspective, microgrids can reduce generation & transmission planning costs; besides, it can serve as an arbitrator to earn additional savings for owners.

Technical – The microgrid can improve the technical performance of the distribution grid in the following aspects: 1) Energy efficiency improvement due to network loss reduction and the utilization of CHP units; 2) Control over power quality via demand side management, coordinated reactive power control and constrained active power dispatch,; 3) Transmission congestion reduction; 4) Ancillary services for supporting grid stability; 5) Grid reliability enhancement via microgrid islanded operation when loss of main grid.

Environmental – The generation in the microgrid leads to a shift towards renewable energy and thus a low GHG emission. On the other hand, the utilization of more energy efficient solutions like CHP and DSM is facilitated by control operation of microgrids.

Social – The microgrid application can raise public awareness and foster incentives for saving energy and reducing carbon emission as well as creating new research topics and job opportunities. For remote or rural regions, the microgrid technology provides a promising solution of electrification.

All the impacts listed above are easy to understand in qualitative aspects but will be less easier to study quantitatively. It is not only because the quantification of microgrid benefits itself is abstract and tentative, but also because it is a multi-objective multi-stakeholder problem where the solution requires some degree of coordination.

1.1.2 Real World Microgrid Demonstration

Figure 1.2 shows a considerable number of research projects to date on microgrids, with many demonstration projects, underway or already commissioned, launched by federal programs, institutions or the private party. Three microgrid examples are highlighted in the following discussion to bring together useful information from the field and to demonstrate the value of microgrids in real-world applications.

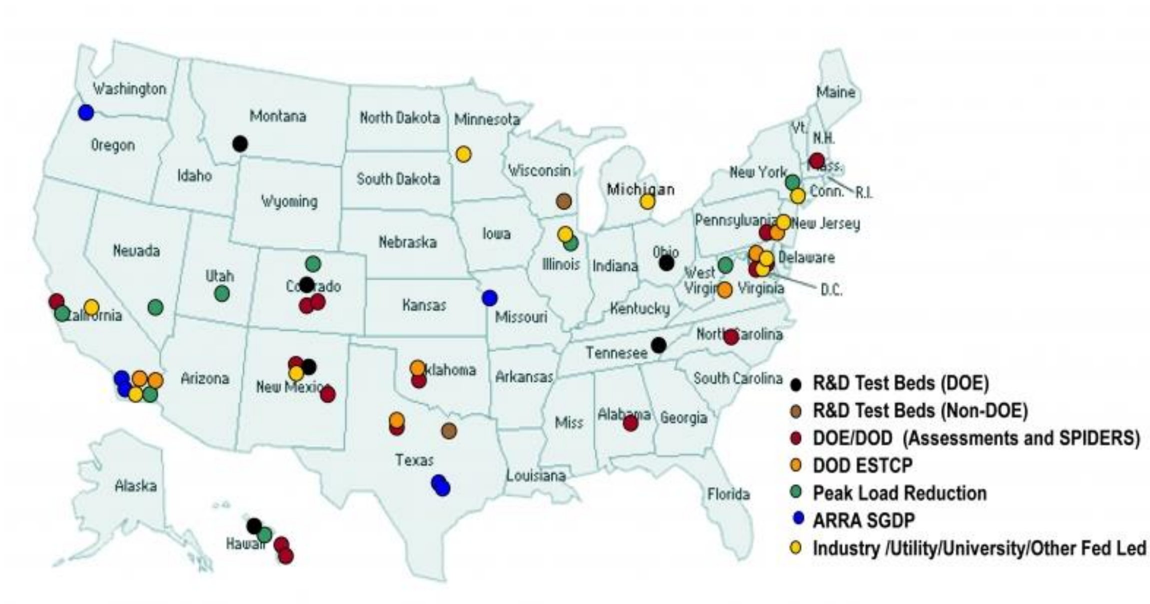


Figure 1.2 DOE microgrid activities in United States [5]

CERTS Microgrid **[6, 7, 8]**

The CERTS microgrid was initiated in 1999 to respond to a call from U.S. Congress to restart a federal transmission reliability R&D program and it was implemented to address the concerns on grid reliability technology [9]. It was demonstrated at a full-scale test bed built at American Electric Power Walnut site near Columbus, Ohio, sponsored by the California Energy Commission PIER Electric Transmission Research Program Its participants included University of Wisconsin-Madison (PSERC), Sandia National Laboratories, Woodward, Princeton Power Systems, Northern Power Systems, Tecogen, and Lawrence Berkeley National Laboratory.

The microgrid site is connected to the utility through a 1.5MVA 13.2kV/480V step-down transformer. As shown in Figure 1.3, two microsources are on Feeder-A, (A-1 and A-2) as well as two loads Load-3 and Load-4. The third microsource, B-1, is on feeder B with a single load Load-5. Feeder C has a single load bank Load-6. These three 60kW Tecogen CHP units, driven by natural gas fed engines, are interfaced by controlled inverters that use a combination of P-f and V-Q droop control. The four load banks can be remotely controlled from 0-90kW and 0-45kVAR. Load-4 also includes a directly connected induction motor with a capacity of 20 HP.

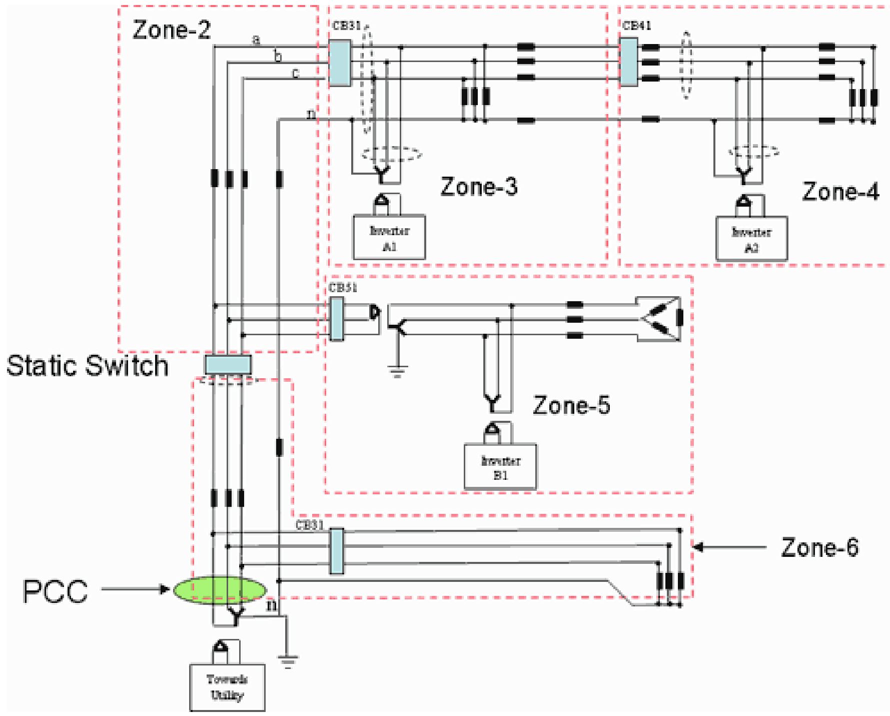


Figure 1.3 CERTS microgrid schematic

The CERTS Microgrid Demonstration accomplished its objective of enhancing the ease of integrating small energy sources into a microgrid by developing three advanced techniques [7, 10]: 1) a method for effecting automatic and seamless transitions between grid-connected and islanded modes of operation; 2) an approach to electrical protection within the microgrid that doesn't depend on high fault currents; and 3) a method for microgrid control that achieves voltage and frequency stability under islanded conditions without requiring high-speed communications.

The IIT Perfect Power Systems

DOE and private industry partners sponsored the Perfect Power initiative, launched by the Galvin Electricity Initiative at Illinois Institute of Technology (IIT) in 2008, together.

The construction of the microgrid involves the entire IIT campus, driven by facts that [11]:

1) The occurrence of at least three power outages per year resulted in a series of teaching and research disruptions with an estimated cost of $500,000 annually;

2) There was a steadily growing demand for electricity in the IIT campus area and it needed to be accommodated by new electric energy facilities.

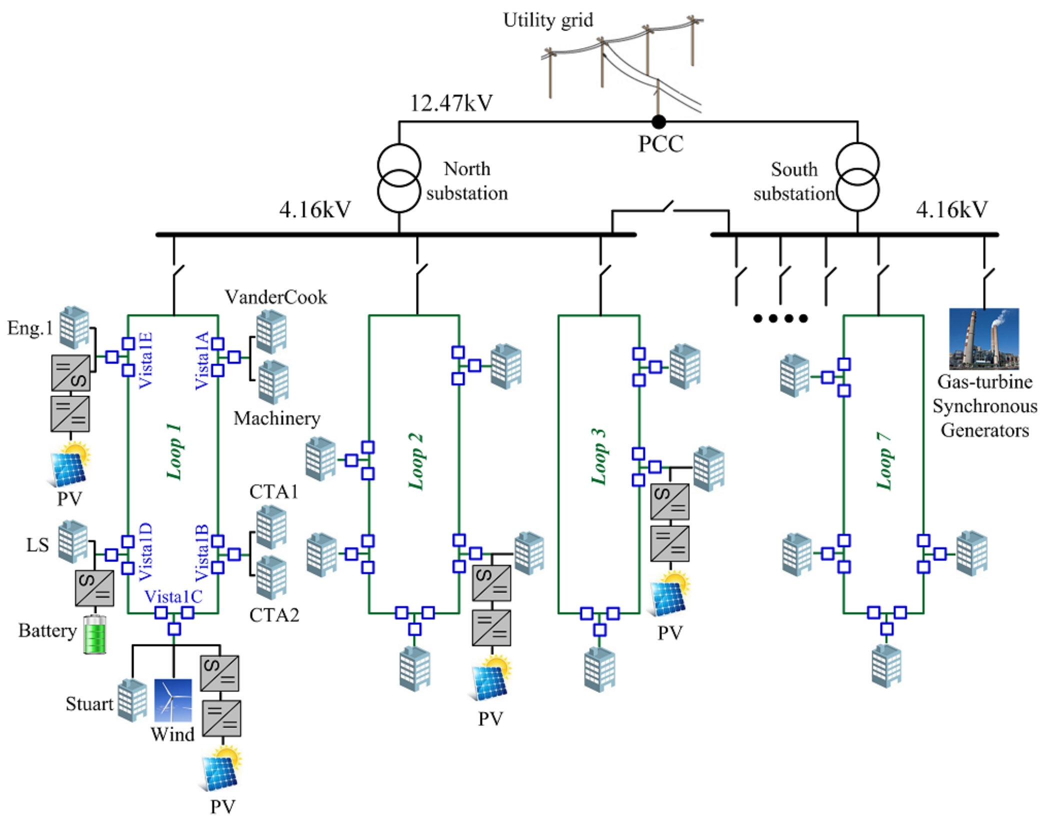


Figure 1.4 IIT microgrid system configuration [11]

Key features of the IIT Perfect Power microgrid include:

1) High Reliability Distribution System (HRDS) is implemented by replacing old radial distribution systems with new redundant looped systems using fully automated switches shown in Figure 1.4. If the disturbance occurs in the loop, it can be isolated by the switches within 6 cycles and the system can still supply power to all the buildings.

2) A three level hierarchical controller, the Intelligent Perfect Power System Controller (IPPSC), is designed to interface, coordinate, and control the actions of building controllers, HRDS controllers and distributed generation controllers inside the campus. Besides, it allows the microgrid to respond to real time pricing of electricity demand through communication outside with ISO and utility. This system coordinates how much electricity is needed and what load services can be deferred or curtailed to reduce peak demand.

3) The on-campus DERs include 8 MW natural gas power plant, 1.5 MW wind unit, rooftop PV as well as 500 kWh flow battery. These renewable generation options give the IIT

microgrid the ability to completely disconnect from the main grid and operate as an island for a short-term period during emergency or major utility disturbances.

***UCSD Microgrid* [12, 13]**

The University of California, San Diego (UCSD) owns a 42-MW microgrid with a master controller and optimization system that self-generates 92% of its own annual electricity load and 95% of its heating and cooling load for a community of 45,000 residents [10]. It saves US$800,000 per month for the UCSD by using the generation of DERs in the microgrid.

This microgrid consists of two 13.5 MW natural gas generators, one 3-MW steam generator, three steam driven chillers, five electric driven chillers and one thermal energy storage (TES) tank with 1.5 MW of behind-the-meter solar PV, as well as 1.4 MW of curtailable HVAC loads. Figure 1.5 shows the resource mix and energy flows of the UCSD microgrid. Heat energy is recovered from the two generators' exhaust to generate steam that is utilized in three aspects: electricity via steam turbine, chilled water via steam driven chillers and hot water via heat exchanger. The TES tank reduces electric chiller operation during SDG&E on peak hours and thereby reduces power production costs by using low-cost, off-peak energy.

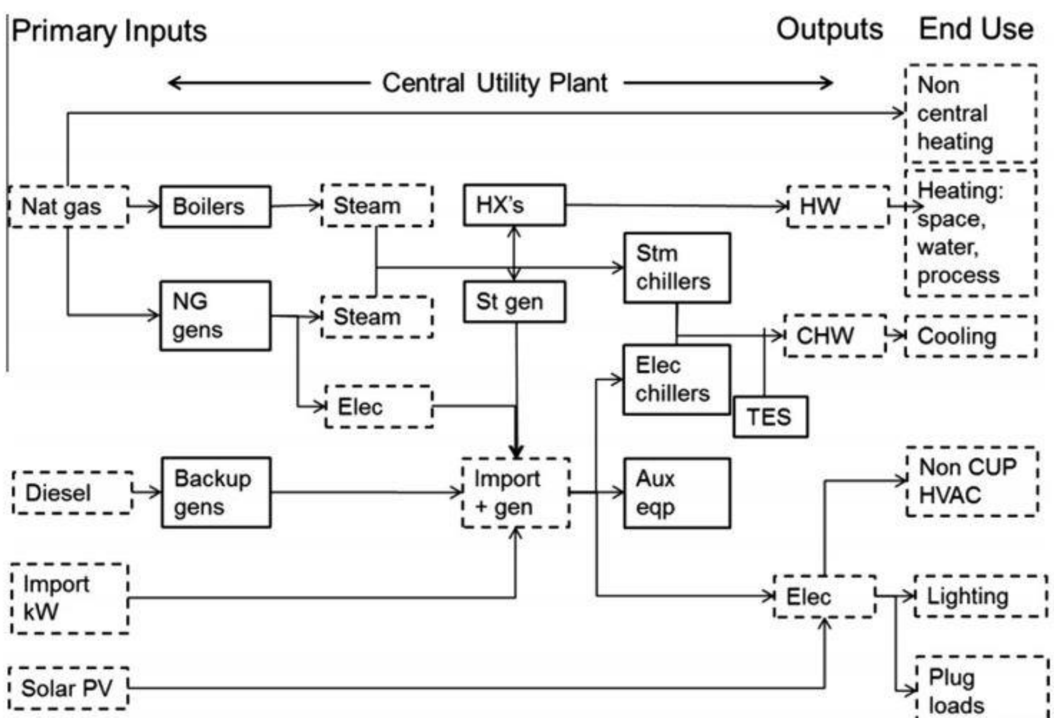


Figure 1.5 Resource mix and energy flows in UCSD microgrid [13]

UCSD, in collaboration with Power Analytics, has developed a microgrid master controller Paladin, which can monitor and control the real time operations of the microgrid and conduct power system analysis to verify reliability constraints for microgrid planning and operation. As a complementary software, UCSD has deployed VPower platform to integrate the UCSD campus diverse renewable portfolios to minimize energy cost and carbon footprint. Both of the solutions ensure that the economic optimization is achieved while electrical constraints are satisfied.

1.1.3 Nested Microgrids

Nested microgrids refer to multiple microgrid zones within the microgrid system that can be operated independently in islanded mode and optimized as a portfolio when grid-connected. This concept is brought based on the fact that the vital services and facilities, such as fire departments and hospitals, are usually dispersed across a wide area in the community. Figure 1.6 shows Olney Town Center is such kind of community with critical services scattered all over the region. In the architecture of nested microgrids, services that are both geographically and electrically close are grouped into one control node and the services in the whole area can be served by a cluster of control groups. During grid outage, each node would serve the facilities with their own distributed generation to increase resiliency while all the nodes would be managed together to maximize economic benefits and provide grid support during normal operations. Another advantage of the nested architecture over single microgrid for the whole area is that it takes full advantage of local underground cables and avoids the cost for undergrounding of overhead lines when overhead forms most of the local backbone systems.

However, the nested microgrid architecture brings complexity to microgrid system planning, modeling and control since there are more PCCs involved in the system, requiring more interconnection and safety equipment than one extensive microgrid.

Figure 1.6 Critical load groups in Olney Town Center [14]

1.2 Microgrid Modeling and Control

1.2.1 Microgrid Modeling [15]

A microgrid system usually includes local distribution feeders, distributed energy resources (DERs), loads, reclosers and switches, power electronic interfaces, control and protection systems, and so on. To investigate system characteristics, perform power system analysis and apply control techniques, a microgrid model is required and it should be able to accurately reflect the dynamics of the real-world system.

As the building blocks of the microgrid, accurate modeling for DERs, such as PV systems, BESS and natural gas generator (NG-GEN), is critical but also challenging because there exists no standard for DER models. Since most of the DERs are connected to the grid via power electronic interfaces, the dynamics of the DERs are strongly coupled with the dynamics of power electronic devices as well as their control strategy, leading to a non-linear complex system. However, new techniques of power electronics modeling and control are being published every year. The number of grid integration methods and control strategies are numerous for each type of DER. Another issue with microgrid modeling is that the assumptions about three phase balanced conditions, such as primarily inductive transmission lines and constant power loads, don't hold valid for microgrids. The microgrid model should be considered as three phase unbalanced system model. The good news is that, for component modeling, there are a few typical representations of DERs that are widely used and proves effective in microgrid system modeling. A description of microgrid system models and component models are introduced in Chapter 2.

1.2.2 Microgrid Control

The microgrid control system is the key to ensure reliable, secure and economical operation of microgrids in either grid-connected or islanded mode so that the microgrid appears as a controlled, coordinated unit to the upstream network. Several most relevant challenges in microgrid control include [16]:

Stability issues: Local oscillations may emerge from the interaction of control systems of DG units. Moreover, the transition between grid connected and islanded mode needs to be done seamlessly.

Low inertia: Unlike bulk power systems where a high number of synchronous generators ensure a relatively large inertia, microgrids might show a low-inertia characteristic since the energy capacitors store is far less than energy stored in rotary shaft of the generators. The low-inertia characteristic in the system can lead to severe frequency deviations in islanding mode when there's only a small mismatch between load and generation, especially when no appropriate control mechanism is implemented.

Uncertainty: The uncertainty of parameters, such as load profiles and weather forecasts, in microgrids is higher than that in bulk power systems due to a reduced number of loads and highly correlated variations of available energy resources. The coordination among different DERs becomes more challenging especially in isolated microgrids.

Desirable features of microgrid control systems include [16]:

Economic dispatch: An appropriate or optimal dispatch of DERs participating in the operation of a microgrid can significantly reduce costs, or increase profits with taking into account other factors like reliability, system efficiency and GHG emission.

Transition between modes of operation: The microgrid should be able to operate in both grid-connected and islanded mode, including a smooth transition between them. Different control strategies might be defined for each mode of operation.

Frequency/Voltage Control: Especially during islanded operation where system stability is sensitive to active/reactive power imbalance, DERs in the microgrid should be able to regulate voltage and maintain frequency within permissible range.

Output Control: Output current and voltage of DERs units should be able to track their reference values with damped oscillation and acceptable latency.

A full description of microgrid control functionality can be found in ORNL use cases, which are discussed in Appendix C.

1.3 Project Background

The work described in this thesis is part of the Olney Town Center Microgrid Project awarded by Department of Energy. The main purpose of the project is to research, develop, model and test a microgrid control system that is able to provide highly resilient electricity services for the Olney Town Center area, located at Montgomery County, Md. The project is studying how such a microgrid would operate in different scenarios in accordance with State and Federal goals.

The Olney Town Center serves as a critical community hub and lifeline, including a hospital, two schools, police and fire stations, a water tower, and other vital services within one square mile. Even though PEPCO, the local utility, has taken many steps to harden the grid, major equipment can be still damaged by storms and other events, resulting in an extended outage. These attributes make the Olney Town Center a good prospect for an advanced community microgrid. A high resilient microgrid at Olney Town Center will provide safety and security values by ensuring the community's ability to provide emergency and essential services during and after an emergency or other outage-causing event.

To manage the nested microgrid, a microgrid controller, namely GreenBus, is designed by the team from Green Energy Corporation to integrate renewable energy resources, natural gas CHP units, BESS, and DSM technologies in near-real-time optimization schemes. The GreenBus system is expected to have the capability of improving reliability measure SAIDI by 98%, while increasing efficiency by at least 20% and reducing GHG emissions by 20% or more.

The role of the FREEDM team in this project is to lead and execute all microgrid control system testing for the project and supports engineering analysis and test results reporting. In other words, the FREEDM team is responsible for setting up a test environment that is able to integrate the microgrid controller and analyze its performance, in order to justify that the designed microgrid controller can support a full microgrid concept and achieve the goal of the project. At the current stage, a full dynamic model for multiple-zone microgrid system is developed and a microgrid testbed that can execute test plans, collect test results and conduct data analysis is established.

1.4 Contents of Thesis

The thesis mainly discusses microgrid model design and validation, microgrid controller test plans and evaluation methodology, test environment setup, and how test results are analyzed.

The fundamentals of the testbed are explored in Chapter 2, including microgrid models and testbed environment overview. The modeling approach, functionality and validation for the multi-zone microgrid system as well as microgrid components are studied, and a brief introduction of testbed environment setup as well as testbed validation is included. In Chapter 3, the test functional requirements are reviewed. Performance metrics and evaluation methodology are described in detail, followed by a detailed description of test plans. Chapter 4 focuses on the implementation of test environment setup. A thorough discussion on test integration, execution and automation as well as post-processing methods is included in this chapter. At the end of Chapter 4, the development of a fully functional test master is discussed. Test results for different use cases such as energy dispatch, are presented in Chapter 5 as well as post-processing analysis. Finally, Chapter 6 gives the conclusion, summarizes the achievements of the thesis and provides recommendations for future work.

Chapter II. Olney Microgrid Testbed

As is mentioned in Section 1.3, the Olney Town Center Microgrid Project focuses on the development of a microgrid control system capable of providing highly resilient electricity services for critical facilities. After the microgrid control system is designed and developed, its functionalities need to be validated through a rigorous laboratory emulation.

The Olney Microgrid testbed, which provides a testing environment for the purpose of validation and evaluation of microgrid controller, is built based on OPAL-RT simulator. Opal-RT provides a distributed real-time simulation platform that can solve power system equations fast enough to continuously produce output conditions that realistically represent conditions in the real network. Because the output is real time, the simulator can be connected directly to power system control equipment and protective relay equipment or interfaced with external equipment or emulators of individual grid subsystems such as distributed generation or energy storage. Therefore, a variety of microgrid control scenarios can be evaluated through a mix of simulation and interfaces of microgrid components.

The FREEDM team has developed a multiple-zone microgrid system model that contains microgrid component prototypes for PV, BESS, and load and NG-CHP units, to emulate the local distribution network. Section 2.1 focuses mainly on the configuration of local distribution systems and microgrids. Component models as well as system models are discussed in Section 2.2. In Section 2.3, the whole test environment is introduced. Finally, verification results of testbed communication are shown in Section 2.4 to demonstrate that the testbed is successfully interfaced to the microgrid controller.

2.1 Overview of Olney Microgrid Design [17]

Figure 2.1 shows that the Olney Town Center microgrid design contains six microgrid zones. However, Zone 4 and Zone 6 are not included in the overall envelope of microgrid controls and thus are not modeled, simulated, or tested in the test environment for current phases. It is because these two zones are located outside the primary microgrid footprint and their loads are small compared to the load of the whole microgrid.

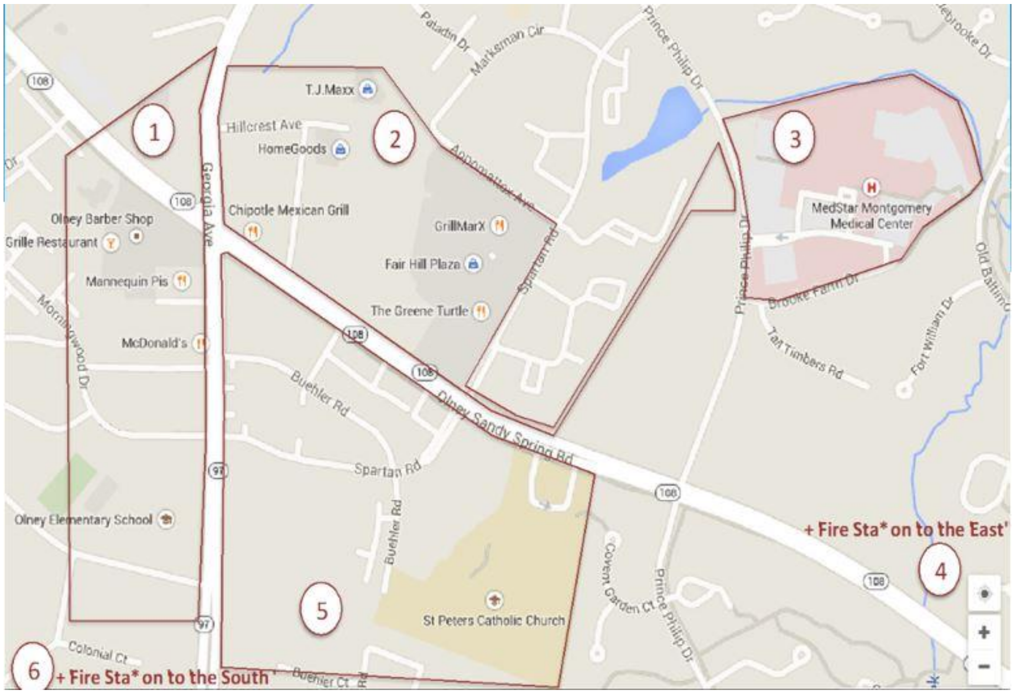


Figure 2.1 Olney Town Center microgrid zones

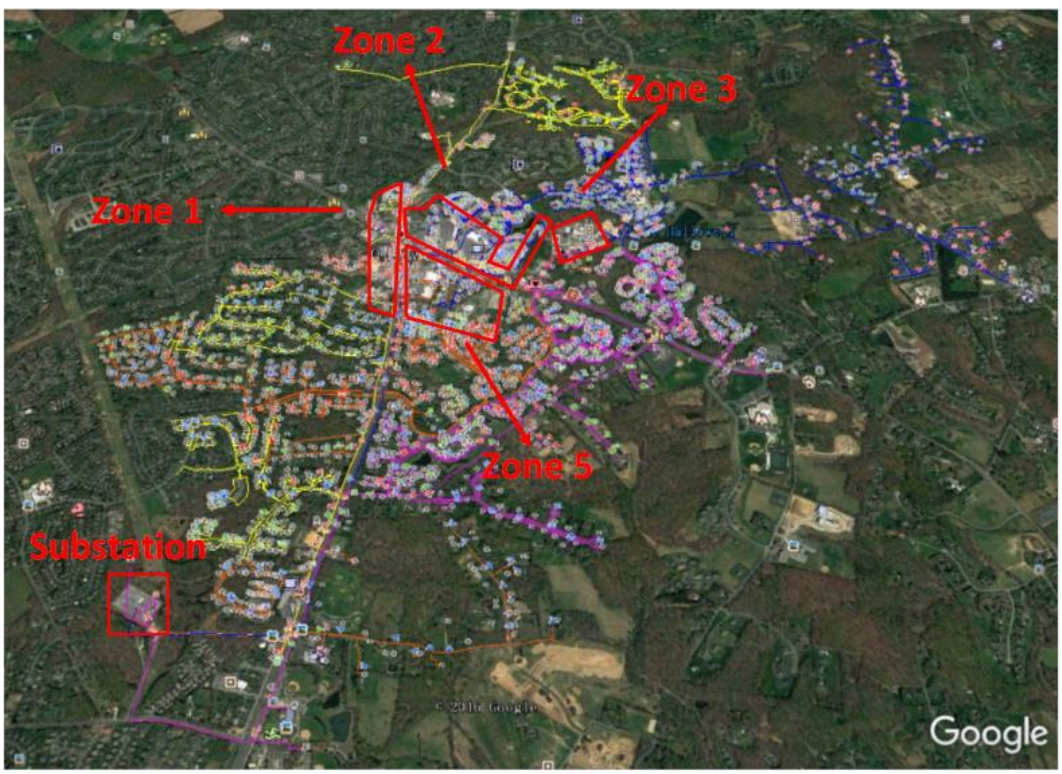


Figure 2.2 Olney distribution systems (orange – feeder 15119, blue – feeder 15125, yellow – feeder 15126, magenta – feeder 15129)

Table 2.1 Mapping on feeders to microgrid zones

	Zone 1	Zone 2	Zone 3	Zone 5
Feeder 15119	√	×	√	√
Feeder 15125	×	√	√	√
Feeder 15126	√	×	×	×
Feeder 15129	×	×	√	×

There are four feeders, all of which are connected to the 13.2 kV substation, serving the Olney microgrid zones. Figure 2.2 shows the GIS information of the distribution feeders, showing that all of four microgrid zones are closer to the end of the feeders. Each feeder serves one or more than one zone and each microgrid zone consists of sections from one or more feeders. The mapping information is described in Table 2.1.

There are several special considerations for microgrid designs. Those considerations include Load Criticality, Resource Portfolio and Grid Reconfiguration, which are discussed further below.

2.1.1 Load Criticality

The primary objective of the Olney microgrid is to provide resilient electricity for critical services, so the selection of critical loads is necessary and needs to be based on some criteria. In the Olney Town Center area, there are a high density of loads that are critical to health, safety and vitality of the Olney community. There also exist substantial loads that provide convenience and shelter and other services that help maintain the community during long-duration outage events, with small loads that generally do not impact the community. Four levels of load criticality are defined as below:

High – important public safety and life-related services that must remain available and continue operations throughout the whole event and even the aftermath;

Medium – critical services that become important within the next 8 to 24 hours from the beginning of the event;

Low – critical services that become important within two days;

Optional – additional retail and other facilities, especially restaurants that can serve the community in the aftermath of the event.

A summary of critical vs noncritical loads is shown in Table 2.2 and the list of criticality of load groups is included in Appendix A.

Table 2.2 Critical load groups vs noncritical load groups

Microgrid Zones	Critical Load kW Peak	Critical Load kW Avg	Noncritical Load kW Peak	Noncritical Load kW Avg	Total Load kW Peak	Total Load kW Avg
1	1,158	390	133	27	1,291	417
2	1,758	961	225	59	1,983	1,020
3	2,611	1,736	0	0	2,611	1,736
5	2,040	1,054	37	12	2,077	1,066
Total	7,567	4,141	395	98	7962	4239

2.1.2 Resource Portfolio

The size of generation and storage is chosen based on all the following assumptions:

- accommodate the critical loads within the microgrid boundary
- support all the critical loads in an island
- support use of flexible load as a resource
- support use of utility grid energy supplies as a variable resource where economically beneficial

Table 2.3 summarizes the total microgrid resource portfolio.

Table 2.3 Olney Town Center microgrid resource portfolio

Resources	Total kW capacity	Description
NG Engine-based CHP	3,480	2*762 kW+2*358 kW+ 5*248 kW with 20T and 30T absorption chillers
Solar PV	1,827	Rooftop PV arrays of various site
Battery Energy Storage	730	Li-ion community energy storage units
NG Generator	150	2*50 kW+2*20 kW natural gas engine generators as base generation supplement to the CHP units
Total	6,187	

2.1.3 Grid Reconfiguration

There are two forms of circuit reconfiguration: (1) permanent reconfiguration to simplify grid-connected operations and transitions between modes, and (2) an islanding reconfiguration that happens upon loss of the main grid.

Since the control system is designed for nested microgrids, which operate as a portfolio when grid-connected and as separate islands upon loss of the distribution system, it is of great importance to know the PCCs of each zone. In the case of Olney circuits, each microgrid zone is assumed to have two types of PCCs: one is at the head of the zone and the other at the tail. The locations of head and tail breakers as well as tie switches can help determine logical PCC locations. Since some of the zones consist of circuits from different feeders, each zone has at least two PCCs. A detailed microgrid system reconfiguration is discussed in the Section 2.2.2.

2.2 Olney Microgrid Modeling

What makes a good microgrid system model? First of all, the test system should be equivalent to the original circuits with the same operating characteristics on buses-of-interest. Then, regarding microgrid components modeling for DERs, loads and transformers, the models that are developed should accurately reproduce the dynamic behaviors of the real world devices. Now that there are a large number of similar elements in the microgrid system under study, the prototype MATLAB/Simulink model is derived for each component. If the modeling for one component is straightforward, the built-in models in Simulink/Simpowersystems libraries are deployed but the corresponding parameters are updated to duplicate the real-world components. The further discussion on component models are given in Section 2.2.1. Section 2.2.2 focuses on how an equivalent reduced model is derived. The reason why a reduced model is required is that the original circuits are too complicated, containing almost 5000 components. Therefore, duplicating the detailed model is time-consuming. Besides, from the simulation standpoint, it’s intractable to process a large scale system at a high time resolution via real time simulators.

2.2.1 Component Model Functionality

Dynamic models are developed in the MATLAB/Simulink environment for photovoltaic (PV) systems, load groups, combined heat and power (CHP) units and battery energy storage systems (BESS) based on the real-life commercial products or existing researches. The models are used for studies on various operating modes of the microgrid controller. To represent the real-world microgrid components as accurately as possible, they are validated by a combination of real-world data as well as established component models. The details of modeling validation approach are described following the discussion on model functionality.

2.2.1.1 PV Systems

Modeling Approach

To simplify the simulation while still being able to capture the features of PV generation, the PV inverter is modeled using an average modeling approach. The whole PV system is modeled as a three phase controllable current source importing power to the grid. The power generated can be controlled to follow any given PV profile.

The block diagram is shown in Figure 2.3. The PV model can be attached to any bus in the grid and can inject power to follow a pre-defined, dynamically changing PV profile. In Figure 2.3, the 'Enable' variable (1 for on and 0 for off) controls the status of the PV. The output power from PV system is measured and logged by a three-phase V-I meter.

Figure 2.4 shows a general structure of the PV system model. Three phase voltage measured at the attached bus is transformed into the dq0 reference frame so that Vq=0. Based on the relationship: P=Ud*Id and Q=-Ud*Iq, the injected active and reactive power can be controlled by controlling the injected currents on both d-axis and q-axis. Also, because the model uses measured terminal voltage in the dq0 reference frame, in conjunction with a phase lock loop controller to determine the correct system frequency, the model is suitable for grid-connected and islanded simulations, where the frequency may vary.

The power reference used for PV system are all real world PV profiles and processed outside the model.

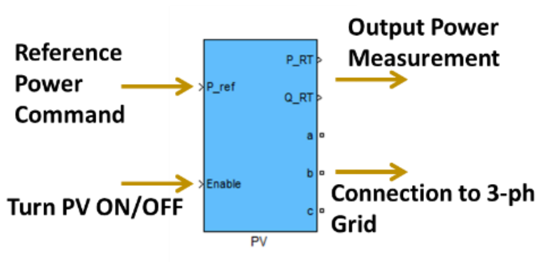


Figure 2.3 PV system block in Simulink

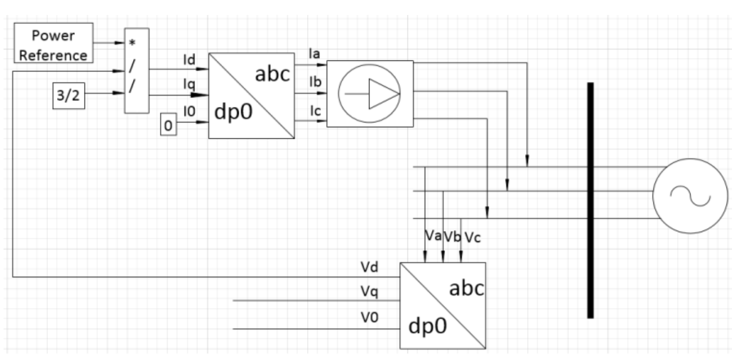


Figure 2.4 PV system general structure

Functionality

- Use real-world 1-minutes solar data to create a solar radiation database;
- Use interpolation to generate real-time database;
- Contain 3 PV profile day types: Sunny, Partial Cloudy, Cloudy;
- Allow random selection of solar profiles;
- Allow the effect of storms and clouds to be added at designated time intervals.

Verification

The model is verified by feeding a random real world PV profile shown in Figure 2.5 to the model. The measured PV system power output is shown in Figure 2.6. We conclude that the model successfully emulated the real world power PV profile reference.

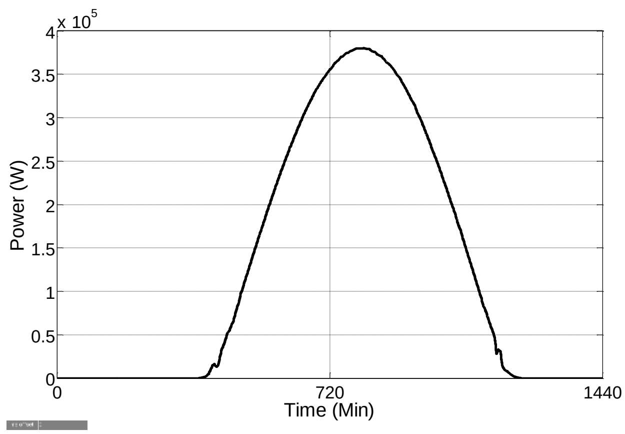


Figure 2.5 Referenced real world PV profile

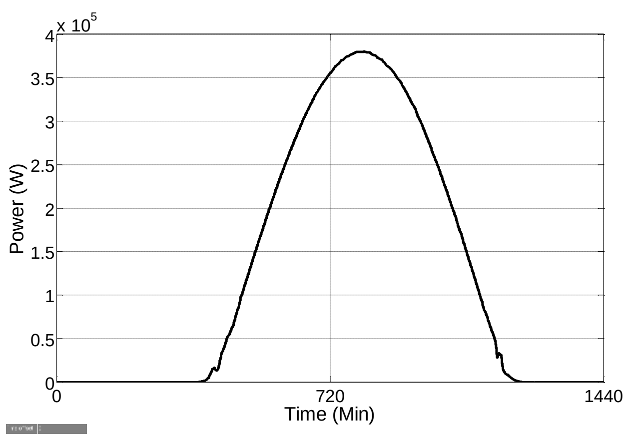


Figure 2.6 Simulated PV system output power

2.2.1.2 Load Group

Modeling Approach

Load groups are modeled as a three-phase controllable current source extracting power from the grid. The extracted power can be controlled to follow any given load profile.

The model is developed in Simulink and the block diagram is shown in Figure 2.7. The model can be connected to any bus in the grid to emulate electric demand. The power flowing from grid to load group is measured as logged data. The power reference used for load groups are all real world load profiles and processed outside the model.

Figure 2.8 shows a general structure of the load group model. The modeling approach is exactly the same with PV systems. The only difference is that in this case, the power reference needs to be negative so that the direction of power flow is from grid to the current source.

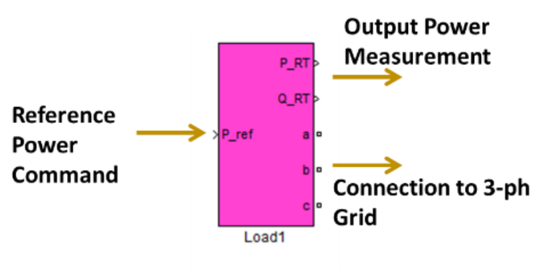


Figure 2.7 Critical load groups block in simulink

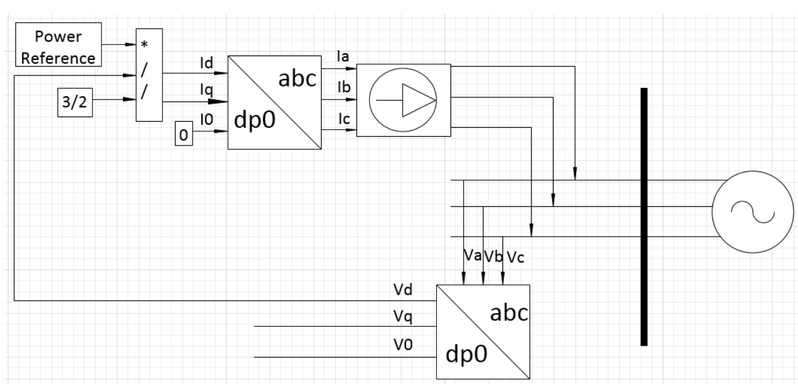


Figure 2.8 Critical load groups general structure

We have different criticality levels modeled for different load groups. Load shedding commands can trip load groups with optional, low and medium criticality. Only the highest criticality loads are modulated by a pre-defined percentage of the whole loads, if needed.

Functionality

- Hourly load data provided by PEPCO and additional 15-minute residential load data based on PNNL field demos;
- Use interpolation to generate real-time database;
- 4 day types: Spring, Summer, Fall and Winter;
- 4 load priorities: High, Medium, Low, Optional;
- Allow selection of load profiles in real-time;
- Allow control set points for load shedding and modulation;
- Allow any level of reactive power.

Verification

The model is verified by feeding to the model a real world load profile provided by PEPCO, shown in Figure 2.9. The measured load group power output is shown in Figure 2.10. We conclude that the model successfully emulated the real world demand profile reference.

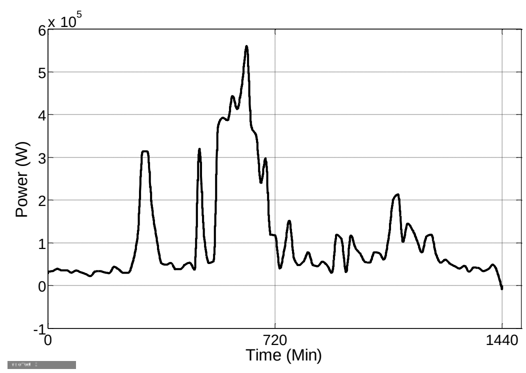


Figure 2.9 Referenced real world load profile

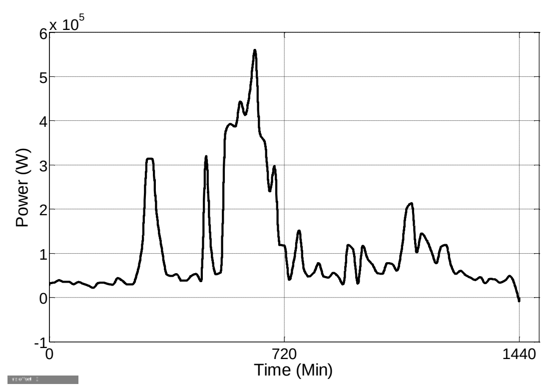


Figure 2.10 Measured load group input power

2.2.1.3 CHP Unit

Modeling Approach

The CHP unit is composed of a 250 kW gas fired micro-turbine, a synchronous generator and an absorption chiller. The micro-turbine consumes the natural gas as the fuel, and by burning the fuel it generates mechanical power to drive the synchronous generator. The generator then provides electrical energy to the load and grid. As a byproduct, the exhaust heat coming out of turbine can be recycled through the absorption chiller to supply cooling or heating loads. Figure 2.11 shows the block diagram of the CHP unit.

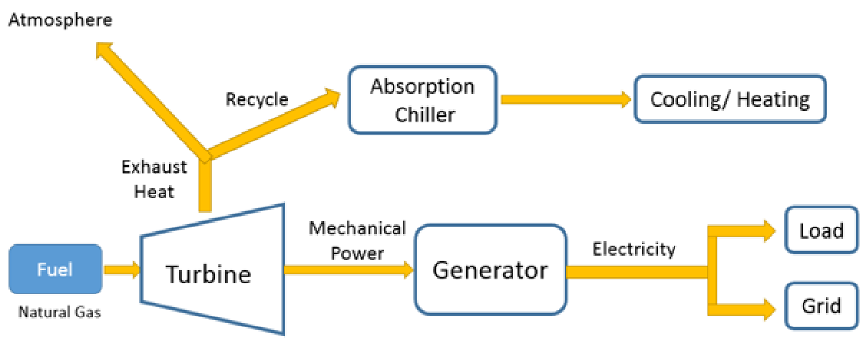


Figure 2.11 Block diagram of a CHP unit

Figure 2.12 shows the dynamic model of the CHP unit developed in Simulink. The micro-turbine unit consists of governor control, temperature control, acceleration control, fuel system, compressor and turbine, as shown in Figure 2.13. Details of simulation parameters regarding the micro-turbine block can be found in [18]. The synchronous generator block consists of the excitation system and the generator.

The following equations show the exhaust heat calculation, where Q_{ex} is the amount of exhaust heat in kW; P_{fuel} is the amount of fuel sent to turbine in kW; p2, q2 are coefficient constants. Absorption chiller is simplified to be the coefficient of performance (COP), where the input is Q_{ex} and output is the cooling capacity. COP for a single-effect ranges from 0.6 to 0.8 while COP for a double-effect ranges from 1.4 to 1.6.

$$Q_{ex} = f\left(P_{fuel}, T_{out}\right) = p_2\left(T_{out}\right) \times P_{fuel} + q_2\left(T_{out}\right) \times \delta$$

$$p_2\left(T_{out}\right) = a_2 \times T_{out} + b_2$$

$$q_2\left(T_{out}\right) = c_2 \times T_{out} + d_2$$

$$\delta = 1 \text{ for CHP on}$$

$$\delta = 0 \text{ for CHP off}$$

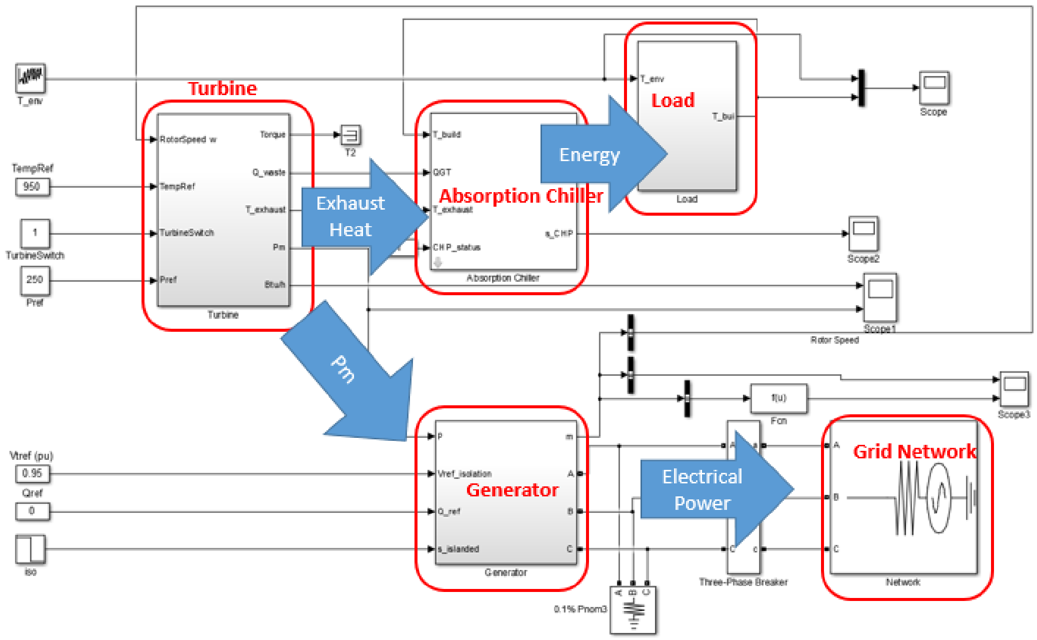


Figure 2.12 Simulink diagram of a CHP unit

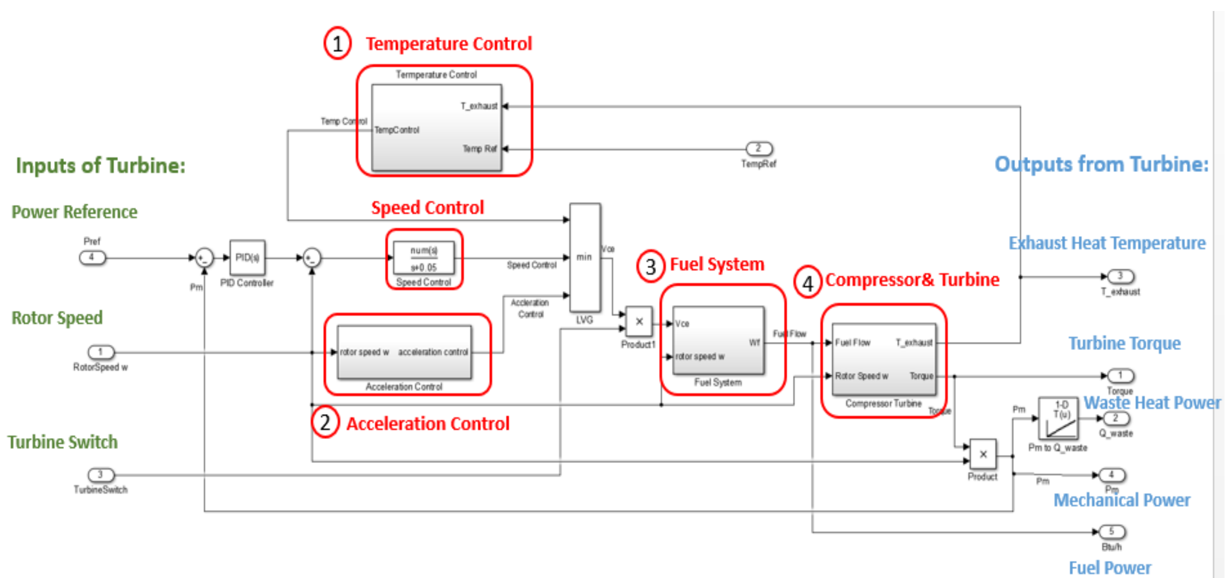


Figure 2.13 Block diagram of the micro-turbine in a CHP unit

Functionality

- Under grid-connected mode, CHP unit delivers real power to the grid based on power reference command;
- Under islanded mode, CHP unit operates in isochronous mode and regulate the terminal frequency;

- Under both grid-connected and islanded mode, CHP unit provides thermal energy to cooling/heating loads.

Verification

Figure 2.14 shows the steady state performance of the CHP that delivers real power to the grid based on power reference command. Note that during hour 15 to hour 19, due to the limit of ambient temperature, the CHP unit cannot output to its maximum capacity.

Figure 2.15 shows the dynamic response of CHP during the islanding event when the CHP unit regulates the frequency of the microgrid when the transition happens at 25s. The speed variation of CHP unit jumps up immediately when grid-connected mode is transitioned to islanded mode and recovers back to one per unit after 7 seconds.

Figure 2.16 shows CHP unit provides thermal energy to cooling/heating loads. The thermal energy output to heating/cooling loads corresponds to CHP output power in Figure 2.14. It can be seen from Figure 2.16 that with the set point shown in Figure 2.14, thermal load demands (orange) exceeds CHP thermal output energy (blue) in the nighttime while there is a surplus of thermal output energy during the day.

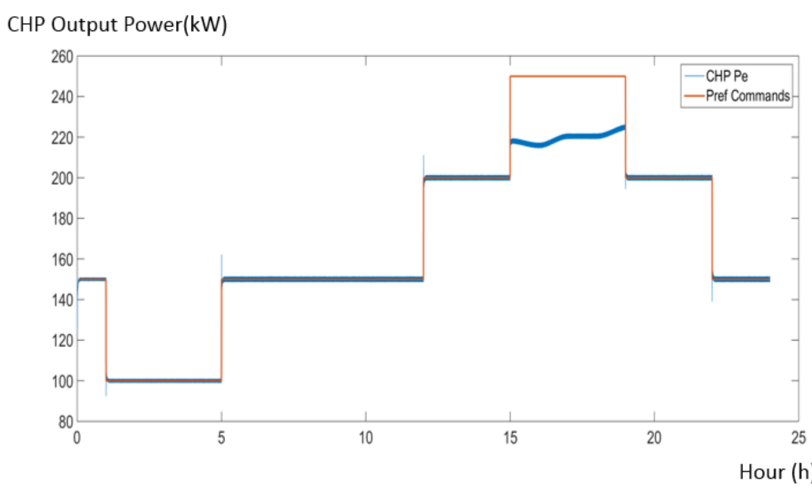


Figure 2.14 CHP electrical output versus power output reference command under grid-connected mode

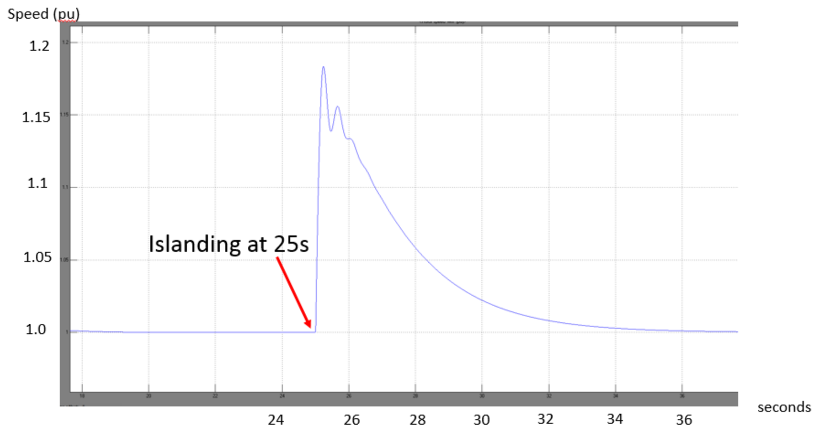


Figure 2.15 Speed response between transitions from grid-connected mode to islanded mode

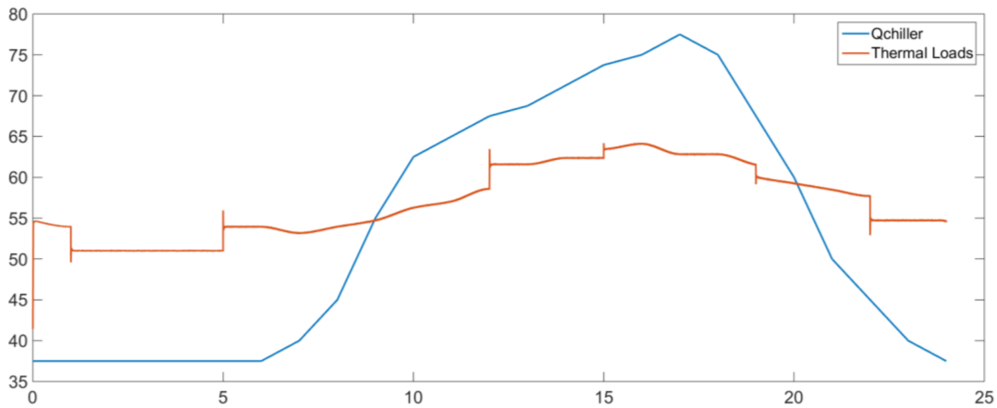


Figure 2.16 Thermal loads versus thermal energy provided by Chiller

2.2.1.4 Energy Storage System

Modeling Approach

The Energy Storage System consists of two parts: battery equivalent model and inverter model. A high-level block diagram is shown in Figure 2.17.

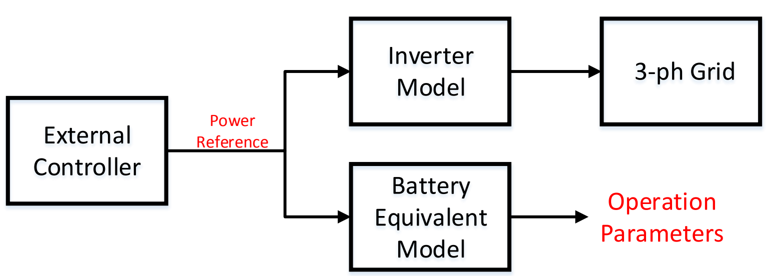


Figure 2.17 Energy storage system model block diagram

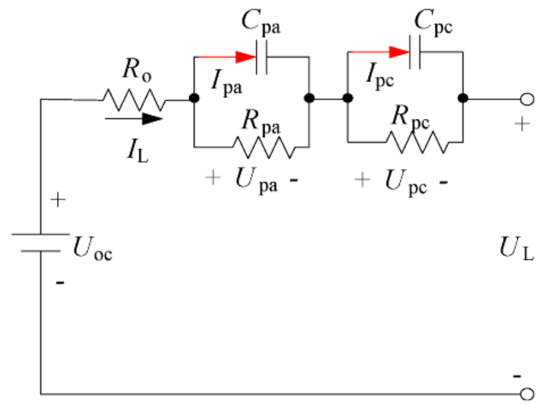


Figure 2.18 Dual polarization battery model

The battery equivalent model is used to simulate the battery's states including the battery open-circuit voltage (Voc), terminal voltage and SOC. A dual polarization battery model is deployed in this case. This is a well-established battery modeling approach [19]. The equivalent circuit is shown in Figure 2.18.

The inverter model is developed based on Schneider Electric BESS grid-connected inverters. The inverter is modeled using average modeling approach. The block diagram is shown as Figure 2.19 below.

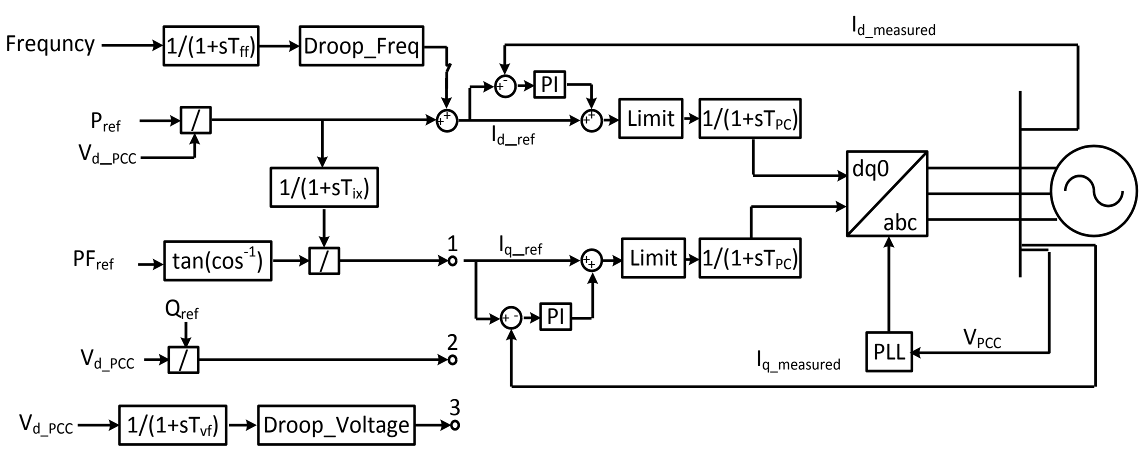


Figure 2.19 Schneider inverter model block diagram [20]

The inverter converts the DC power provided by the energy storage to AC power at three-phase AC nominal output voltage. The model presented is intended to produce simulation results that closely approximate the response of the plant to these disturbances, and do not in any way represent the physical implementation of the specific inverter or plant control algorithms.

Functionality

- Battery operation states (SOC, Voc, etc.) are simulated and monitored using battery equivalent model;
- Three general modes of inverter operations are provided, as follows:
  1. Constant Power Factor (QMODE = 1): In this mode, the desired imaginary, or reactive, current Iq_ref is varied in direct proportion to the desired real (active) current Id_ref to maintain a constant power factor, derived from the initial conditions in the power flow solution, throughout the duration of the simulation.
  2. Constant Reactive Power (default, QMODE = 2): In the default mode, the desired imaginary (reactive) power stays constant throughout the simulation by varying the imaginary (reactive) current Iq_ref in inverse proportion to the terminal voltage. The value of reactive current is derived from the initial condition in the power flow solution.
  3. Voltage Control (QMODE = 3): In this mode, the desired imaginary (reactive) power is dependent on the terminal voltage Vd_PCC based on the specified Q-U dead band and droop characteristic. This function becomes active if the terminal voltage Vd_PCC is outside of the specified bandwidth. In such case, the inverter's reactive current Iq_ref varies as a linear function of terminal voltage, according to the characteristic of Figure 2.20 below. The user defines the slope and bandwidth of the Iq-V characteristic.

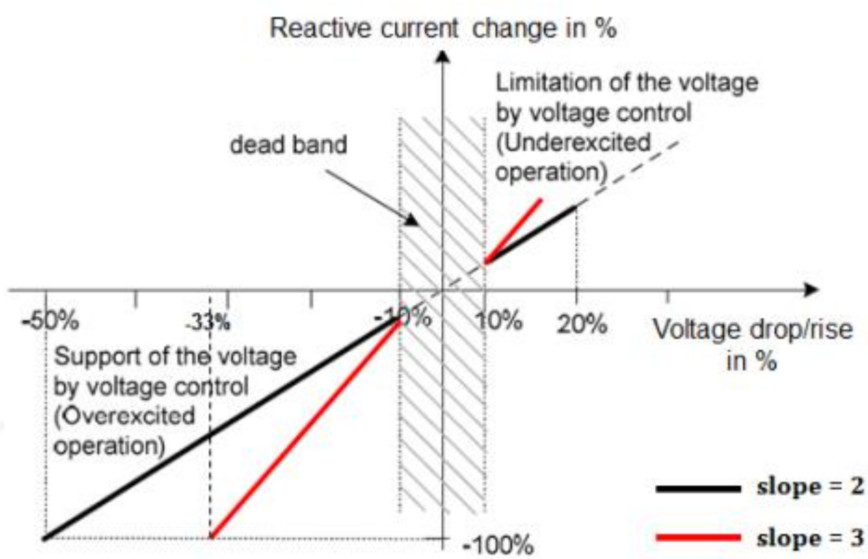


Figure 2.20 I_Q-V characteristic of the voltage control function [20]

In addition to these three modes, another mode is Frequency Regulation. In this P-F mode, the desired real (active) power is depended on the system frequency based on the specified P-F dead band and droop characteristic. This function becomes active if the frequency is outside of the specified bandwidth. In this case, the inverter's active current I_{d_ref} varies as linear function of frequency. Similar to the Voltage Control mode, the user defines the slope and bandwidth of the I_d-F characteristic.

Regardless of the mode of operation, current limiting is applied to I_{d_ref} and I_{q_ref} to limit the apparent current, with reactive current given priority over active current. The real and reactive components of current are aligned with the generator bus voltage angle by means of a fast acting phase locked loop (PLL).

Verification

The verification of dual polarization battery model can be found in [19].

The verification of inverter model is included in [20].

2.2.2 Distribution System Modeling

As shown in Figure 2.2, the Olney distribution circuits within the primary microgrid footprint are four feeders with thousands of electrical components. The development of a full model with such complexity requires a great deal of time and effort, and moreover, its simulation needs significant computational power. The model is designed for studying microgrid operations under different scenarios, so circuit details outside the microgrid footprint are not modeled. Considering the impact of an upstream fault on microgrid protection equipment, the upstream utility system is simplified into a Thevenin equivalent circuit. The microgrid system is kept in detail using a reduced circuit in order to reduce the modeling effort without any impact on the characteristics of microgrid system. A circuit reduction method is applied on the system and the model is developed based on a combination of resources, including utility network KMZ models, CYME models, microgrid design models, and refinements from utility engineering department.

Circuit Reduction Method [21]

To begin the circuit reduction, the buses of interest that will remain in the equivalent circuit must be selected. These buses of interest can be a user-selected option. In our case, we keep as buses of interest the PCCs for all four microgrid zones, as well as critical load buses and the buses connecting to renewable generation. After the buses-of-interest are identified, all other buses in the feeder can be removed or reduced to branches or laterals.

Next, all the nodes that don't contain load or generation are removed. Under simple cases with a single line going through the node, the equivalent line is the sum of impedances on either side. This technique is applied to the whole distribution system. If the bus is part of a network where there is a branch split or there are multiple lines, the bus will not be removed until the next iteration of reduction.

Then, an equivalent impedance is placed to represent the upstream utility network ending at microgrid head PCC, with a dummy load representing the downstream circuit from tail PCC. The reduction technique assumes that all the upstream loads, either on the backbone feeder or at laterals, are too small compared to the loads within the microgrid boundary to impact the voltage drop. Therefore, we ignore upstream loads and combine upstream laterals. Eventually, the upstream equivalent impedance equals to the sum of the impedances of the upstream backbone feeders.

For the laterals within the microgrid boundary but not between the buses-of-interest, we combine those laterals by placing their loads on the point of interconnection. For the laterals within the microgrid boundary that contain buses-of-interest, the junction points also become buses-of-interest because laterals that did not have buses-of-interest were already removed. In cases where the lateral has the buses that contain non-critical loads, these laterals can either be combined by placing all the loads on the nearest upstream bus-of-interest or be removed if the loads are small.

Using the method mentioned above, reduced equivalent models are derived for all the microgrid zones and feeders. The reduced one-line-diagram for the distribution feeders is shown in Figure 2.21 and a detailed model for microgrid Zone 1 is shown in Figure 2.22. The models for the rest of the zones, along with system parameters, are included in Appendix B.

Figure 2.21 shows that the system is reconfigured in a way such that each microgrid is operated radially when connected to the grid. The orange block represents microgrid Zone 5 that consists of two subsections. It connects to the upstream utility through a normally-closed PCC head breaker. Besides, Zone 5 has two interconnections via normally-open PCC breakers, one of which goes to the downstream Zone 1 and the other of which goes to Zone 2 from another feeder. Zone 2, represented as a red block, connects to the upstream circuit through a normally-closed PCC head breaker and connects to Zone 5 and Zone3, respectively, via two normally-open tail breakers. Zone 1, the green block, has one normally-closed PCC head breaker going to the utility substation and one normally-closed PCC tail breaker going to the downstream circuits. Also it connects to the upstream Zone 5 through a normally-open breaker and connects to the downstream Zone 3 through a normally-open breaker. There are three subsections in Zone 3 that are interconnected together through normally-closed tie switches. Zone 3 has in total three PCC head breakers but only one of them is the normally-closed breaker that connects to the utility. The other PCC head breakers are normally-open interconnections to Zone 1 and Zone 2.

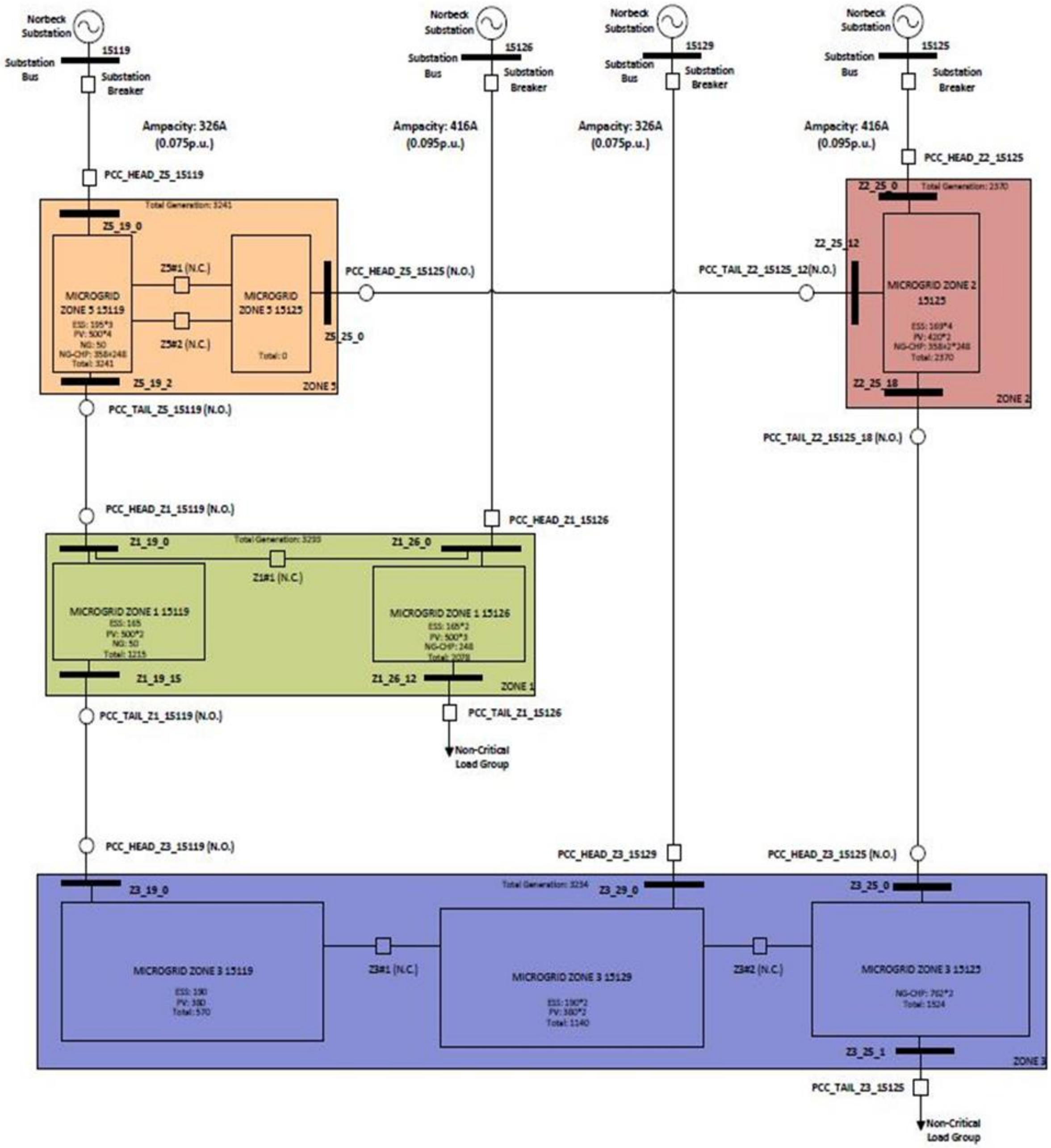


Figure 2.21 Olney Town Center microgrid master one-line diagram

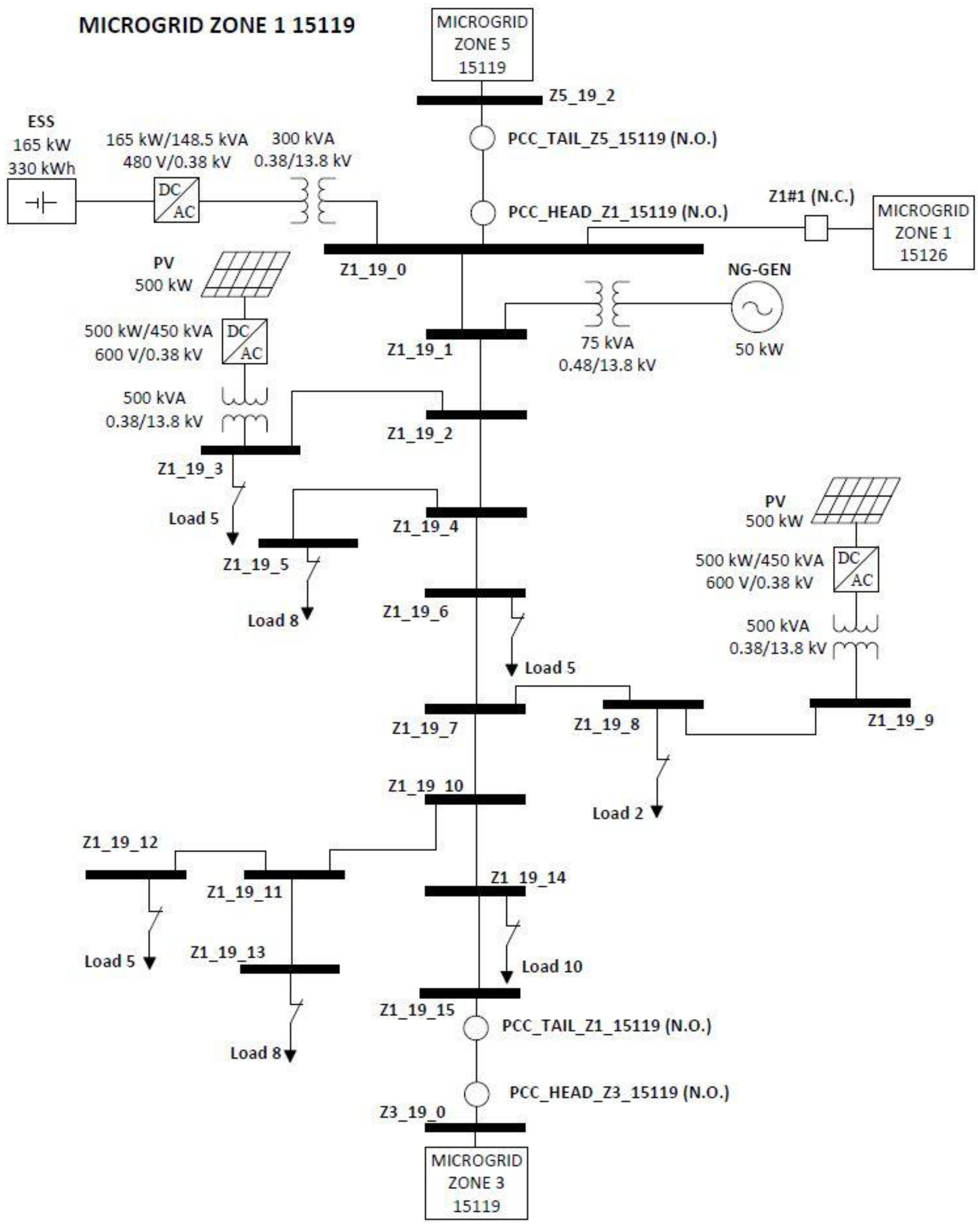


Figure 2.22 Olney microgrid Zone 1 - feeder 15119

Verification

A short circuit analysis is conducted on the reduced microgrid model. As shown in Table 2.4, the fault currents on several PCCs match well with the results generated by running short circuit analysis on the full CYME mode. It proves that the reduced model derived using circuit reduction technique is equivalent to the original circuit.

Table 2.4 Comparison of short circuit values between full and reduced models

Fault Location	3 phase fault (kA)			line to ground fault (kA)		
	Full Model	Reduced Model	Error	Full Model	Reduced Model	Error
Substation	23.610	23.101	2%	25.610	24.906	3%
Z5-19-0	5.867	5.052	14%	3.941	3.568	9%
Z1-26-0	5.730	6.568	15%	3.926	3.622	8%
Z2-25-0	4.890	5.254	7%	3.304	3.377	2%
Z5-25-0	3.032	3.140	4%	4.527	4.977	10%

2.3 Testbed Environment Setup

As introduced in Section 2.1 and 2.2, the FREEDM Microgrid Testbed is a multiple-zone microgrid model that runs in real time on the OPAL-RT real time platform. In addition to the microgrid model, techniques are needed not only to integrate microgrid controller that remains to be validated and evaluated, but also to operate the testing in an automatic fashion. The setup of test environment is shown in the Figure 2.23.

The DNP3 protocol is utilized to emulate communication in the field for data acquisition and control. When a real-time simulation is running, the testbed supports a DNP3 outstation interface that communicates with the MMC. This allows the testbed to send out system states to the controller for monitoring and control purposes, and to receive control commands from the microgrid master controller.

The TestDrive Interface, developed by Opal-RT Technologies Inc., is the software used to support data acquisition, parameter control, and testing automation. During the real time simulation, TestDrive can acquire system measurements and parameters from the microgrid model. Also, it can send signals to the model and change its parameters. This allows testers to trigger data-logging functionality in the microgrid testbed as well as setting up event modeling and test-initialization parameters. If needed, the test can be automated using the Python script language supported by TestDrive.

The details about microgrid controller integration and TestDrive implementation are discussed in Chapter 4.

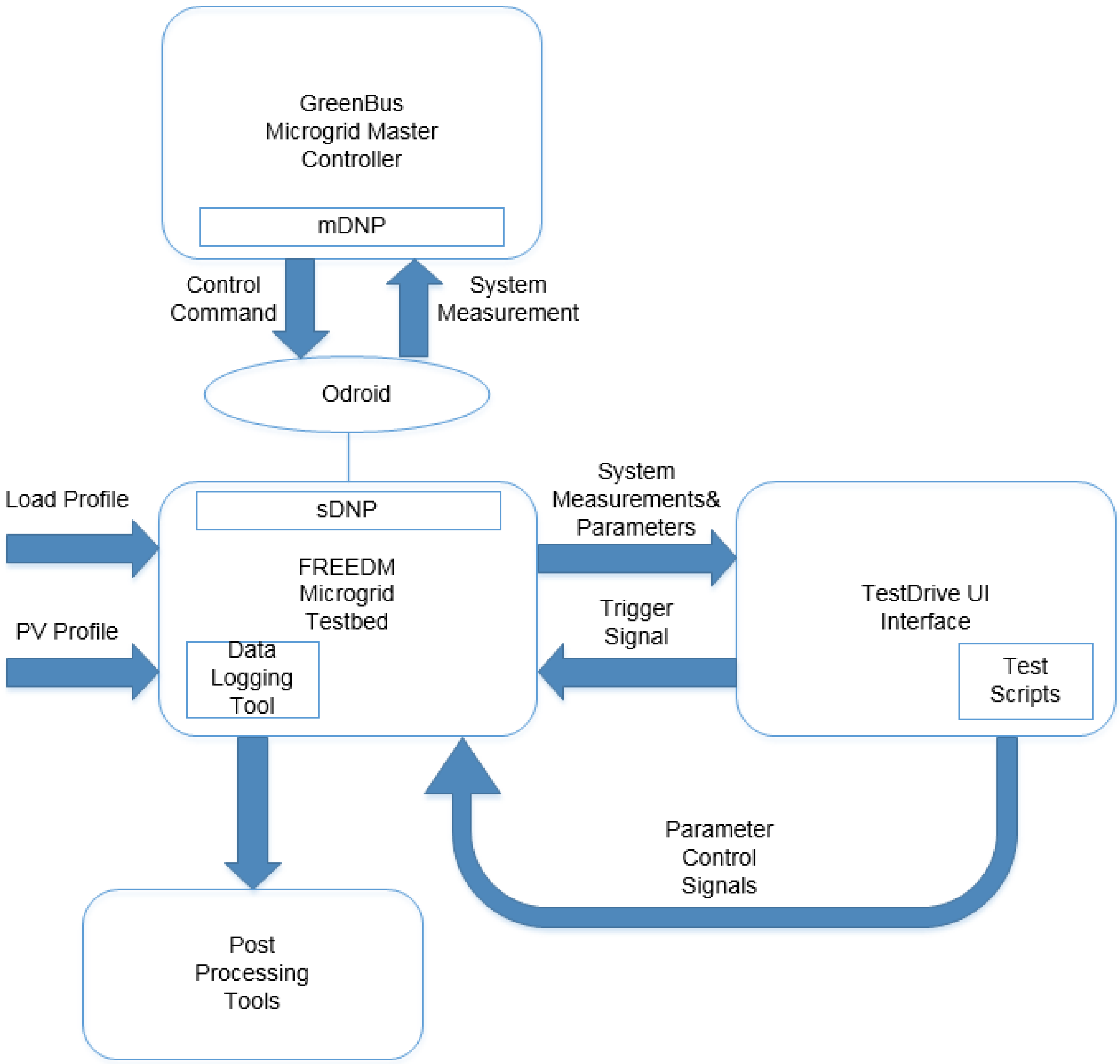
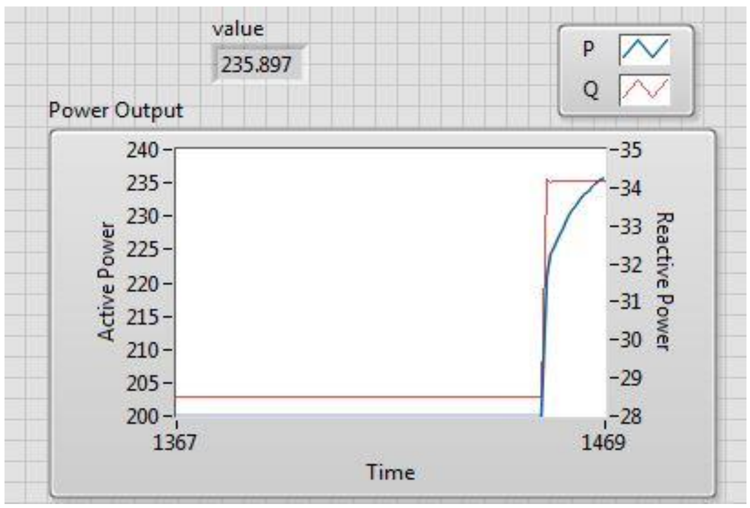


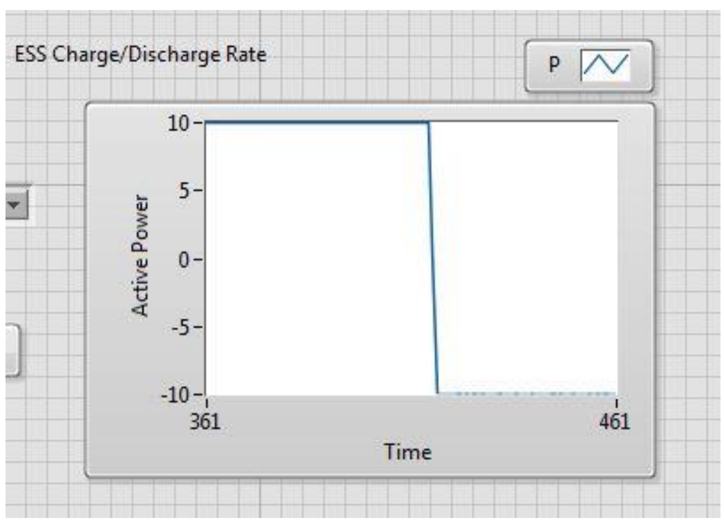
Figure 2.23 FREEDM microgrid test environment

2.4 Testbed Functionality Verification

Two cases are shown in Figure 2.24 to demonstrate that the FREEDM microgrid testbed successfully integrates microgrid controller. In the first case, CHP dispatch command is sent by microgrid controller to set CHP output power from 200kW up to 240kW; in the second case, BESS charging/discharging target is sent by microgrid controller to set BESS from 10kW (discharging) to -10kW (charging). These results show that microgrid controller is able to effectively operate microgrid system model.



(a)



(b)

Figure 2.24 Communication test validation: (a) CHP dispatch value from 200kW to 240kW (b) BESS charging/discharging rate from 10kW to -10kW

Besides the two cases mentioned above, Figure 2.25 shows a long-term steady state simulation where the controller is dispatching CHP and BESS. The results are captured and plotted using data logging function and post-processing tools in the testbed. It shows that the current testbed has the capabilities to integrate the interface to the microgrid controller, record metrics and analyze data. Additional test results are presented in Chapter 5.

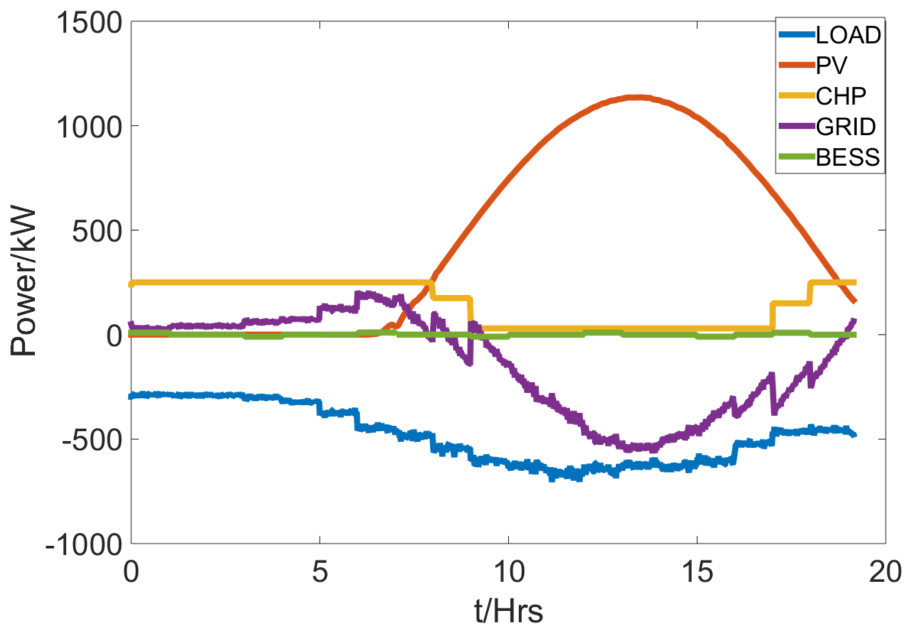


Figure 2.25 Energy dispatch – long-term simulation

Chapter III. Olney Microgrid Test Protocols

3.1 Overview of Test Plan and Functional Test Requirements

The test plan defines procedures utilized for validation of the core functional requirements of the microgrid controller in order to support the performance targets set by the Department of Energy, which are defined as follows [17]:

- reducing outage time of critical loads by >98% at a cost comparable to non-integrated baseline solutions (such as an uninterruptable power supply (UPS) with backup generator);
- reducing emissions by >20%; and
- improving system energy efficiencies by >20%.

These performance targets are to be measured during test execution of use cases that are used to define the triggers, actors, and functions required by the microgrid system and specifically the microgrid controller. The definition of use cases mainly refers to the ORNL test cases, which are included in Appendix C.

Table 3.1 identifies various functional test cases that are used to determine whether the controller meets the performance objectives. Each functional test case will be performed multiple times under defined variations to extrapolate performance for the entire year.

Table 3.1 Table of functional test cases

Primary Functional Test Cases	Microgrid Modes	Objectives (Metrics)
Energy Management	Grid	>20% reduction in emissions >20% improvement in system energy efficiencies >98% reduction in outage time of critical loads
Energy Management	Island	>20% reduction in emissions >20% improvement in system energy efficiencies >98% reduction in outage time of critical loads
Ancillary Services – Demand Response	Grid – Ancillary Services	>20% reduction in emissions >20% improvement in system energy efficiencies >98% reduction in outage time of critical loads
Ancillary Services – Power Management	Grid – Ancillary Services	>20% reduction in emissions >20% improvement in system energy efficiencies >98% reduction in outage time of critical loads
Intentional Islanding – Stability	Transition to Island	>98% reduction in outage time of critical loads
Unintentional Islanding – External	Transition to Island Triggered by External Faults	>98% reduction in outage time of critical loads
Unintentional Islanding – Internal	Transition to Island Triggered by Internal Faults	>98% reduction in outage time of critical loads

Table 3.1 (Continued)

Primary Functional Test Cases	Microgrid Modes	Objectives (Metrics)
Island-to-Grid Transition	Transition to Grid	>98% reduction in outage time of critical loads
Microgrid black start	Startup Ready	>98% reduction in outage time of critical loads
Cyber Security	Grid	>98% reduction in outage time of critical loads

3.2 Performance Evaluation Methodology for Commercial Microgrid Controller

Efficiency, reliability and emission are three primary metrics for evaluating how well a microgrid controller performs. In this section, numerical forms of these three objectives are explored and constructed with a set of necessary measurements defined. Also we illustrate how the metrics are computed from the perspective of testing.

3.2.1 System Energy Efficiency

Microgrid architectures will improve system energy efficiency for two reasons: (1) Since microgrid enables the integration of distributed energy resources that are located close to loads, power flows in transmission and distribution circuits are reduced, so are the losses, leading to a higher system efficiency; (2) the utilization of CHP units in microgrid application can greatly improve the total energy efficiency because waste heat previously rejected to the atmosphere is made use of to provide heat for local use, thus increasing fuel-to-electricity efficiency.

According to the efficiency target proposed by DOE, it should be demonstrated that after deployment of the microgrid and its controller, the system efficiency is improved by at least 20% from that in the baseline case. The baseline is defined as the scenarios where current electric distribution system involves no distributed generation.

To identify the efficiency metric, we firstly discuss the concept of system energy efficiency. In power transmission and distribution systems, the energy efficiency is defined as total power delivered to the consumers divided by the total power output produced by the generators. This measure reflects how much losses occur in the stage of lines and transformers in the grid [22]. The overall losses between the power plant and users can easily be between 8% and 15% [23].

On the generation side, the efficiency of a generator or power plant is usually expressed as a percentage of the amount of energy generation to the power transmission lines divided by the amount of energy used by the generator or the power plant. It considers the losses caused when the fuel is being converted into heat or electricity. Generally, the efficiency of a thermal power plant is around 40% [24]. Therefore, most of the systems deliver electricity to users at an overall efficiency of under 40%.

A reasonable metric for evaluating microgrid system efficiency should combine both of the concepts and is shown as below:

$$\eta = \frac{\sum_{i=1}^{n} E_{load}}{\sum_{j=1}^{m} E_{input}}$$

E_{load} ---- Energy Consumption of Critical Load Groups;

n ---- The Number of Critical Loads;

m ---- The Number of Resources including utility;

E_{input} ---- Energy Input to Resources.

This definition of system efficiency accounts for losses in generation as well as transmission and distribution. Note that energy consumption refers not only to electricity demand but also to heat consumption. Energy input to resources should include electricity and fuel use, with all converted to kWh from other units like BTU or Joule. The format of a testing record sheet for efficiency calculation is shown in Table 3.2.

Table 3.2 Microgrid efficiency test results

Baseline Efficiency	Critical Load (kWh)	Component Efficiency	Energy Input (kWh)
Grid	[Test Data]	40%	[Test Data]
Microgrid Efficiency	Energy Production (kWh)	Component Efficiency	Energy Input (kWh)
PV	[Test Data]	[Test Data]	[Test Data]
BESS	[Test Data]	[Test Data]	[Test Data]
NG-CHP	[Test Data]	[Test Data]	[Test Data]
Grid	[Test Data]	40%	[Test Data]
Average Microgrid Efficiency	[Test Data]	[Test Data]	[Test Data]
Efficiency Improvement	[Test Data]		

To calculate efficiency metric, the simulation should capture the measurements below:

- CHP output power
- CHP fuel use
- PV output power
- BESS charge/discharge rate
- Grid-side imported power (baseline and microgrid)
- Load consumption

3.2.2 Reliability

The DOE resiliency objective is a 98% reduction in outage time for critical loads. In our case, the SAIDI index is used as the approximation of average reliability of utility service for resiliency evaluation. The SAIDI is a measure of how many interruption hours an average customer will experience over the course of a year [25]. The formula is shown below:

$$SAIDI = \frac{\sum CustomerInterruptionDurations}{TotalNumberofCustomersServed} hour / yr$$

Assumptions

1. Based on utility GIS information, we assume all the microgrid zones don't have internal reclosers except for feeder 15126 in Zone 1. For the microgrid zones that don't have internal switches, permanent faults will be isolated based on distribution system protection schemes when they occur inside the zones.
2. If temporary fault occurs, regardless of where it is, the microgrid won't transition to islanded mode, and disturbances seen by the customers will only depend on the locations of reclosers and protection relays. All the fuses are set to fuse savings mode. In other words, temporary faults won't affect SAIDI values.
3. Due to lack of individual customer information, we estimate the number of customers in a load group by assuming it is proportional to load size.
4. The failure rates and MTTP on overheads and UG cables are assumed according to data in [25] and PEPCO's average SAIDI (175.3 minutes/customer/year [17]) (See Table 3.3).
5. Microgrid zones are modeled to utilize existing as-built distribution systems and to demonstrate reliability improvements with microgrid implementation only, before considering additional system improvements, such as segment undergrounding and internal switch additions, to achieve enhanced resilience and support a 98 percent improvement in customer reliability.
6. Natural gas service is maintained during all utility grid outage scenarios.

Table 3.3 Reliability of distribution components

Conductor Type	Failure Rate (counts/mile)	MTTP (hrs)
Overhead Main Lines	0.36	4
Overhead Laterals	0.36	4
UG cables	0.05	10

Fault Locations

We take Feeder 15126 in Zone 1 for example to illustrate reliability analysis. In the diagram, the UG cables are marked in blue and overheads are represented in magenta. Within the microgrid zone, there is a recloser in the middle of section Z1_26_04 and four laterals, two of which are overheads and the other are UG cables.

Four types of fault locations are considered:

- Fault Location 1: Upstream Utility Circuit
- Fault Location 2: Upstream Overhead Primary of Internal Recloser

- Fault Location 3: Section Between Z1_26_0 and Z1_26_2 on Lateral 1
- Fault Location 4: Lateral of Load 1&6&7 Between Z1_26_5 and Z1_26_6 on Lateral 2

We only consider three types of internal fault locations because the Olney outage map, shown in Figure 3.1, indicates that from 2009 to 2015 there was a small chance that a fault would happen at other locations within the zone except Location 2, 3 and 4. Therefore, we assume that failure rate is negligible at other locations which are not shown in Figure 3.1.

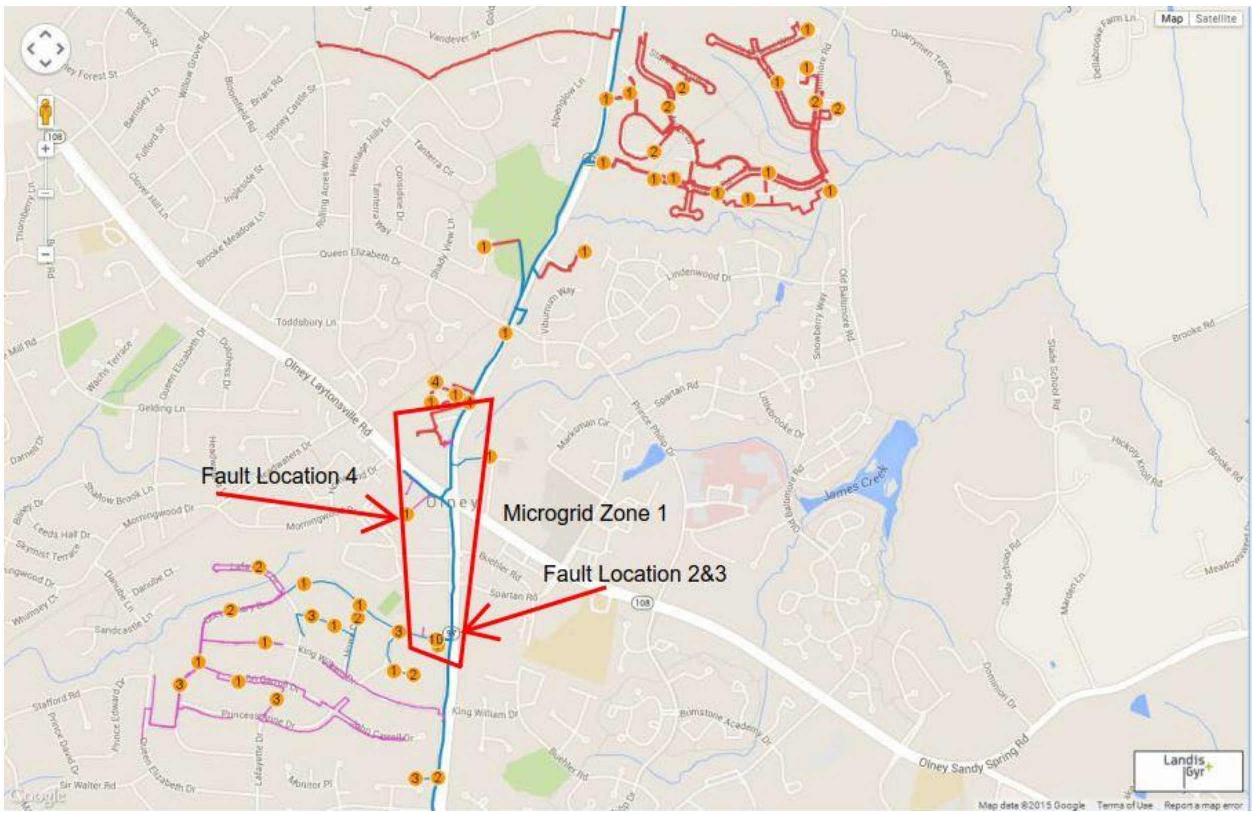


Figure 3.1 Outage map for feeder 15126

Figure 3.2 gives a detailed description of where the fault locations are with respect to microgrid Zone 1. When a fault occurs at Location 1, the microgrid will transition to islanded mode and maintain all the critical services. When fault occurs at Location 2 or 3, it will be isolated by the PCC head and internal recloser, and only lateral 1 will experience outage. When fault occurs at Location 4, the nearest fuse will blow and only downstream customers will be affected.

The distribution of customers is shown in Table 3.4. The number of customers is estimated based on average load consumption. Though the values seem small, they nevertheless produce weighting factors for calculating SAIDI. If there are multiple locations for one critical load group, we assume each location has the same number of customers.

Table 3.4 Customers distribution information

Load Group Number	The Number of Locations	Number of Customers at Each Location	Total Number of Customers
Group 1	2	3	6
Group 3	3	8	24
Group 4	2	1	2
Group 6	1	7	7
Group 7	1	5	5
Group 9	2	3	6
Total			50

Testing Evaluation Approach

To evaluate the performance of microgrid controller on enhancing reliability, tests from three use case tests (Unintentional Islanding-External, Energy Management-Islanded, and Transition-to-Grid-Connected) will be evaluated in post-process analysis to show how many customers can still be served in the aftermath of the faults under the supervision of microgrid controller. For example, if a fault occurs in the upstream circuit, reliability is determined by whether the microgrid controller can successfully transition to islanded mode and manage resources to maintain critical load. If load modulation or load shedding is required during islanded mode, then reliability metrics will degrade. Test data showing load not served will be recorded in the format described in Table 3.5 and used to calculate outage time in various event scenarios, and those metrics will be compared to baseline results shown in Table 3.6 to produce a percentage reduction in outage time and equivalent improvement in SAIDI values.

If results initially fail to meet the DOE objective of reducing outage time for critical loads by >98 percent, then the results of reliability tests will be evaluated to identify design revisions that may be required to provide enhanced resilience and satisfy the outage-time reduction requirement. Examples of enhancements to achieve greater resilience may include upgrading distribution laterals to underground cables, installing more internal switches in the field to increase flexibility of circuit reconfiguration, and expanding DER capacity to meet critical load requirements. Applicable use-case tests then will be repeated using the revised model to verify a 98 percent reduction in outage time. This iterative process is necessary to economically prioritize investments required to assure service for critical loads, supporting the DOE objective to achieve performance outcomes at a cost comparable to non-integrated UPS/backup power solutions.

Enhanced Resilience Evaluation Approach

The test team will evaluate enhanced resilience by including a long-duration outage variation among the Energy Management – Islanded use case tests. Specifically, the test run will simulate an ice storm during the month of February, resulting in a fault at Location 1 for a duration of 10 days. Such a variation will include winter daily load patterns and low PV generation, demonstrating microgrid performance in a major storm-related outage scenario. Resilience metrics will show service maintained to critical loads during this long-duration grid outage.

To calculate reliability metric, the simulation should capture the measurements below:

- Amount of loads being shed for each load group
- Outage duration for each load group

Table 3.5 Microgrid reliability test results

Fault Location	Number of Events	MTTP (hrs)	The Number of Customers Being Served	The Number of Customers Not Being Served
1	0.652	4	[Test Data]	[Test Data]
2	0.054	4	[Test Data]	[Test Data]
3	0.017	4	[Test Data]	[Test Data]
4	0.027	4	[Test Data]	[Test Data]
SAIDI (min/customer/year)			Target	3.5
			Test Result	[Test Data]

Table 3.6 Baseline performance analysis (no microgrid)

Fault Location	The Number of Events	MTTP (hrs)	The Number of Customers Being Served	The Number of Customers Not Being Served
1	0.652	4	0	50
2	0.054	4	0	50
3	0.017	4	0	50
4	0.027	4	35	15
SAIDI (min/customer/year)			175.3	

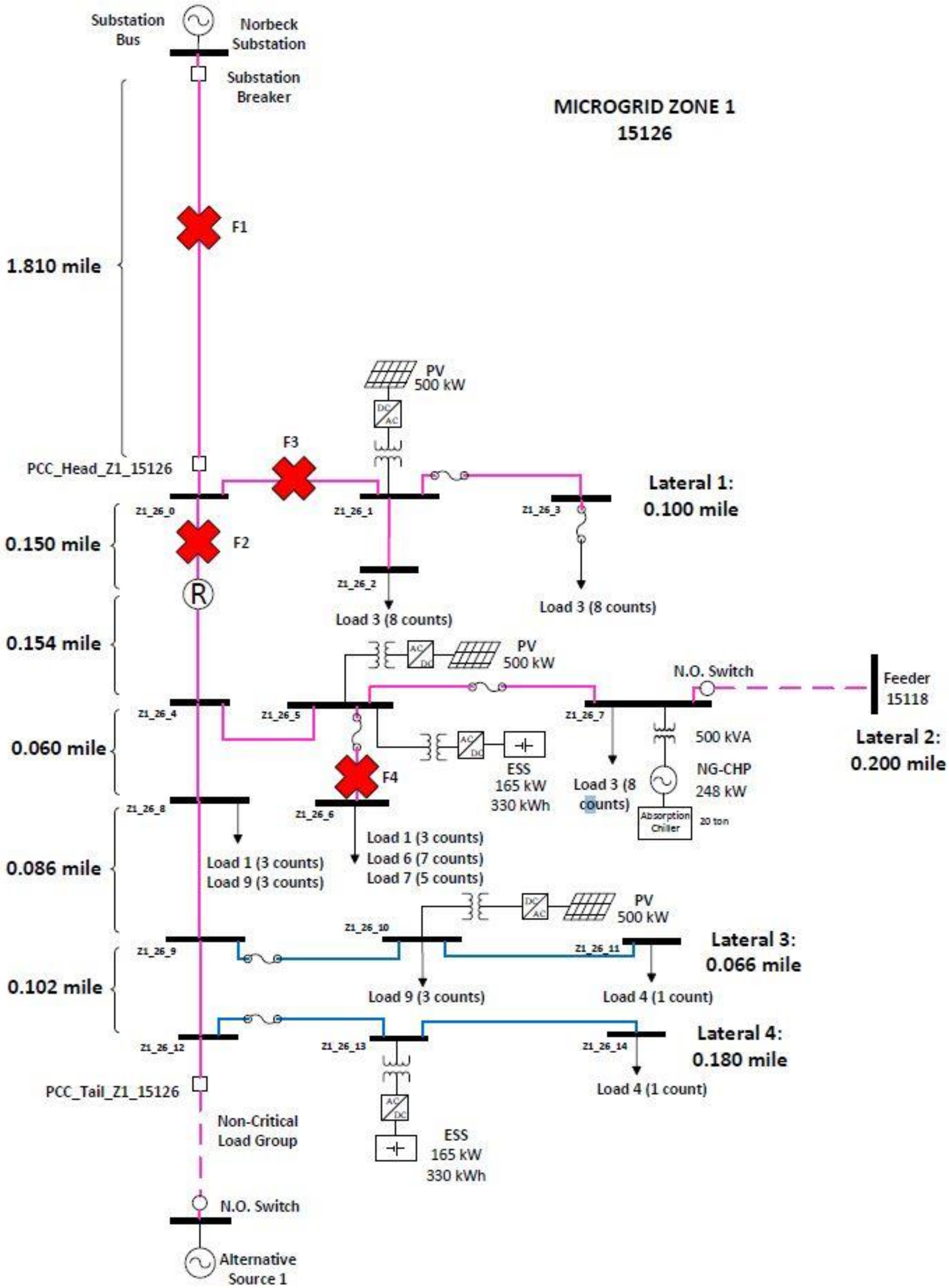


Figure 3.2 Microgrid Zone 1 one line diagram for reliability analysis

3.2.3 Greenhouse Gas Emission

The DOE has the objective of reducing the CO2 footprint of the microgrid area by greater than 20% from the current baseline. This reduction can be achieved by displacing energy supplies from the utility generation portfolio with distributed energy resources having greater amounts of high-efficiency clean generation (natural gas CHP) and non-emitting renewable energy resources.

There are two approaches that are widely used in electric utilities [26]:

Marginal emissions factors (MEFs) are used to quantify avoided CO2 emissions. They reflect the emissions intensities of the marginal generators in the system --- the last generators needed to meet demand at a given time, and the first to respond given an intervention. For specific regions, we calculate the change in fossil generation (G) and change in emissions (E) between one hour and the next:

$$\Delta G_h = G_h - G_{h+1} \left(\mathrm{MWh}\right)$$

$$\Delta E_h = E_h - E_{h+1} \left(kg\right)$$

Using linear regression techniques, the slope of a linear regression of ΔE on ΔG estimates the average MEF. This definition can be applied to a general database that contains data for multiple years, or subsets of the data. For example, monthly MEFs are obtained via using 12 separate regressions of ΔE on ΔG for observations in each month and daily MEFs are obtained via using 24 separate regressions of ΔE on ΔG for observations within a given hour.

Average emissions factors (AEFs) are widely used for evaluating the emissions of either the components or the system. In our case, the AEFs are used instead of MEFs since the marginal generator concept does not apply to our microgrid test system which has one CHP unit. The AEF metrics are derived based on the knowledge of emissions from each component and computed by dividing total emissions by total energy production for a specific time interval.

The format of a testing record sheet for emission calculation is shown in Table 3.7.

Table 3.7 Microgrid Greenhouse Gas test results

Baseline Grid CO2 emissions	Tons/MWh	Total MWh	Total CO2 (Tons)
Grid	0.504	[Test Data]	[Test Data]
Microgrid CO2 emissions	Tons/MWh	Total MWh	Total CO2 (Tons)
PV	0	[Test Data]	0
CHP - NG	[Test Data]	[Test Data]	[Test Data]
BESS	0	[Test Data]	0
NG Generator	[Test Data]	[Test Data]	[Test Data]
Grid	0.504	[Test Data]	[Test Data]
Total Microgrid emissions	[Test Data]	[Test Data]	[Test Data]
Emission Reduction Rate	[Test Data]		

To calculate GHG emission metric, the simulation should capture the measurements below:

- CHP CO2 emission
- CHP output power/energy

3.3 Test Variation

Test variations, listed in Table 3.8, are a set of testing conditions in which each test is established. Test variations are significant for test plan design because test plans should be diverse enough to cover as many system conditions as possible in order to evaluate how well the microgrid controller operates the system or handles the contingency. The variation categories include day type, load type, PV cloudy type, failures of components, events, load change, and test time and duration.

To extrapolate test results to show microgrid performance on a whole year basis, it would be necessary to include peak load day, average load day and low load day for all seasons. PV cloudy types are included to account for the impact of intermittency of PV power output on system states. The variations, like failures of components, events and load change, will put stress on the system and challenge the operation of microgrid controller.

Table 3.8 Summary of test variations

Test Variation Categories	Description
Day Types	Seasons, actual load level are used: peak, average, and low.
PV Cloudy Types	Sunny, partial cloudy, cloudy, rainy
Failures of Components	CHP, PV, BESS, Communication
Events	PV shading, loss of grid supply, frequency dip, grid-side fault, microgrid-side fault, sudden load drop, and sudden grid disconnect.
Load Change	Large motor startup, HVAC loss

A more specific description of variations with coding scheme is shown below in Table 3.9. Each variation category is assigned a unique capital letter, while each variation is assigned a number. The coded variations are used for the convenience of test plan setup and testing automation.

The representative day for each day type is identified and included in Appendix D.

Table 3.9 Test variation coding scheme

Category Code	Test Variation Categories	Variation Code	Variations
A	Day Type	1	Spring peak day
		2	Summer peak day
		3	Fall peak day
		4	Winter peak day
		5	Summer average day
		6	Winter average day
		7	Spring min kWh day
		8	Fall min kWh day
		9	Spring max kWh day
		10	Spring average kWh day
		11	Summer max kWh day
		12	Summer min kWh day
		13	Fall max kWh day
		14	Fall average kWh day
		15	Winter max kWh day
		16	Winter min kWh day
B	PV Cloudy Type	1	Sunny
		2	Partial cloudy
		3	Cloudy
		4	Rainy
C	Failures of Component	1	CHP trip
		2	PV trip
		3	BESS trip
		4	Communications lost with hosted system

Table 3.9 (continued)

D	Events	1	PV shading
		2	Loss of grid supply
		3	Frequency dip
		4	Internal fault
		5	External fault
		6	Sudden load drop
		7	Sudden grid connect
E	Load Change	1	Large motor startup
		2	HVAC loss

3.4 Design of Test Protocols

Testing will analyze microgrid performance for each day type and how it meets the performance objectives, and then tests will extrapolate performance for the entire year of 2014. This approach will allow the testing to be segmented and allow for realistic variations, as shown in Table 3.8. For instance, when energy management in islanded operation is tested, tests are executed against each day type, some of which are run under specific variations. If in some tests, critical loads may have to be shut down and the microgrid may have to go to black start mode, it will negatively affect the performance metrics and should be factored into the extrapolation of reliability metrics. Then we can learn how many events can occur during the year before the performance metric is violated.

Five test protocols are presented based on the test cases described in Table 3.1. Each use case consists of initialization steps, test variations, triggers, actions, expected states, time resolution, metrics, data collected, pass and failure criteria, and post-processing guidelines. A summary of test procedure is included in Appendix E.

3.4.1 Energy Management – Grid Connected

Description: Tests will validate the controller's ability to optimally dispatch microgrid resources. This test plan focuses on grid-connected operations, based on a multi-objective optimization scheme that accounts for reliability, economics, and environmental impact. Tests will account for microgrid resource operating characteristics, resource status, load forecasts, and external pricing signals.

Table 3.10 Energy management - grid connected test procedures

Initialization Steps	Run initialization script with test variation inputs
Test Variations	(A1:A16, B1), (A2, B4), (A2, C1:C4)
Triggers	Grid connected Top-of-hour start computation
Actions	Controller will generate a new forecast every 60 minutes and produce a new dispatch schedule every 15 minutes
Expected States	Resources should be dispatched according to dispatch schedule
Time Resolution	100 microsecond simulation and DER control modeling 1 second OPAL-RT data logging 2 second MMC data capture
Metrics	Amount of emission (tons of CO2) saved during test Efficiency improvement vs grid Cost ($) of operation and savings vs grid Min / Max of available generation for critical load in microgrid
Data Collected	Customer load PCC import / export CHP generation during test PV generation during test BESS state of charge Cost of electricity from the grid CHP fuel use

Table 3.10 (continued)

Pass / Fail	Each Run Microgrid operation is optimized based on predefined objectives without violating constraints Capture cost savings per run Total of Runs Emission calculations within range Efficiency calculations within range Cost savings vs. baseline run with no microgrid operation
Post Processing	Each test produces a 24-hour run based on specific days. In post processing, these days will be extrapolated for one year that is equivalent to the overall energy consumption of Zone 1. The total year will be used to determine the pass/fail criteria. Factors are based on wholesale PJM prices and the cost of natural gas. This will be averaged to show the cost per kWh.

3.4.2 Energy Management – Islanded

Description: Tests will validate the controller's ability to optimally dispatch microgrid resources during islanded mode while maintaining the stability. Islanded-mode operations are based on a multi-objective optimization scheme that accounts for reliability, economics, and environmental impact. In these tests, reliability will be the highest-weighted priority objective. Islanded-mode tests will account for microgrid resource operating characteristics, resource status, load forecasts, estimated outage duration, and generation and load balancing with sufficient reserve.

Table 3.11 Energy management - islanded test procedures

Initialization Steps	Run initialization script with test-variation inputs
Test variations	(A1:A16, B1), (A2, B4), (A2, C1:C4), (A4, E1:E2)
Triggers	Islanded mode operation Top-of-hour start computation
Actions	Controller will generate a new forecast every 60 minutes and produce a new dispatch schedule every 15 minutes Controller will shed and modulate load if required Islanded mode enabled
Expected States	Equipment should be dispatched according to dispatch schedule PCC frequency and voltage should be maintained within certain range
Time Resolution	100 microsecond simulation and DER control modeling 1 second OPAL-RT data logging 2 second MMC data capture
Metrics	Dynamic stability Outage duration for critical loads Amount of emission (tons of CO_2) saved during test Efficiency improvement vs grid Cost ($) of operation and savings vs grid Min / max of available generation for critical load in microgrid

Table 3.11 (continued)

Data Collected	Dynamic Stability Loads not being served Outage duration for critical loads Customer load PCC import / export CHP generation during test PV generation during test BESS state of charge Cost of electricity from the grid CHP fuel use
Pass / Fail	Each Run Stability is maintained; if not, reliability degradation should be included Load shedding and modulation actions are appropriate Capture cost savings per run Total of Runs Reliability performance within range Emission calculations within range Efficiency calculations within range Cost savings vs. baseline run with no microgrid operation
Post Processing	Each test produces a 24 hour run based on specific days. In post-processing, these days will be extrapolated for one year that is equivalent to the overall energy consumption of Zone 1. The total year will be used to determine the pass/fail criteria. Factors are based on wholesale PJM prices and the cost of natural gas. This will be averaged to show the cost per kWh.

3.4.3 Intentional Islanding – Stability

Description: The purpose of this test group is to validate the controller ability to provide an active solution that drives the microgrid ready for islanding. In other words, the controller should guarantee PCC power flow close to zero so that there's a minimum impact of transition on the stability of both microgrid and grid operation.

Table 3.12 Intentional islanding - stability test procedures

Initialization Steps	Run initialization script with test variation inputs
Test Variations	(A5, B4, E1:E2), (A5, B4, C1:C4)
Triggers	Islanding request from distribution system operator or microgrid operator due to foreseen disturbances or maintenance
Actions	Controller will firstly check whether there are appropriate resources from generation and load such that power exchange at PCC is below the threshold. Then it will execute the new dispatch command, trip the switch, and change the modes of DG from grid-connected to islanded. After transition, controller will generate a new forecast as appropriate and produce a new dispatch schedule.
Expected States	Equipment should be dispatched according to dispatch schedule Controller should manage the resources to maintain microgrid stability Islanded mode enabled
Time Resolution	100 microsecond simulation and DER control modeling 200 microsecond OPAL-RT data logging 500 millisecond MMC data capture
Metrics	Dynamic Stability Loads not being served Min / max of available generation for critical load in microgrid
Data Collected	Dispatch schedule to support stability Transition times from the simulator PCC frequency and voltage Customer load PCC import / export CHP generation during test PV generation during test BESS generation during test

Table 3.12 (continued)

Pass/Fail	Islanding is successful based on each test variation Timing limits for islanding honored (less than 160ms) Load shedding and modulation reduction is appropriate given generation capability and forecasts.
Post Processing	Data captured by OPAL-RT will be reviewed to evaluate the transitions during the time of islanding. The generation output will be captured from the controller prior to the islanding and after. For each trigger following the islanding event the controller changes will be logged along with the OPAL-RT data to observe the effects.

3.4.4 Unintentional Islanding - External

Description: The purpose of this test group is to validate the controller ability to enter island mode based on external actions. Without a specific sequence of events for islanding, the stability of the microgrid is at greater risk. The controller will attempt to manage the risk in this test plan.

Table 3.13 Unintentional islanding - external test procedures

Initialization Steps	Run initialization script with test variation inputs
Test Variations	(A6, D2), (A5, D3), (A5, D5), (A5, D3, C1:C3)
Triggers	PCC(s) open due to external protection issue
Actions	Controller will trip non-critical loads in few cycles to maintain the frequency and voltage. Meanwhile, DGs are set to islanded mode with system being re-optimized.
Expected States	Equipment should be dispatched according to dispatch schedule Appropriate load shedding and modulation should be executed Islanded mode enabled
Time Resolution	100 microsecond simulation and DER control modeling 200 microsecond OPAL-RT data logging 500 millisecond MMC data capture
Metrics	Dynamic stability Loads not being served Min / max of available generation for critical load in microgrid
Data Collected	Transition times from the simulator PCC voltage and frequency Customer load PCC import / export CHP generation during test PV generation during test BESS generation during test

Table 3.13 (continued)

Pass/Fail	Controller transitions to islanded mode Controller verifies protection settings Controller develops new dispatch schedule Load shedding and modulation reduction is appropriate given generation capability and forecasts
Post Processing	The data captured by OPAL-RT will be reviewed to evaluate the transitions during the time of islanding based on external fault. The generation output will be captured from the controller prior to the islanding and after. During the islanding event the controller changes will be logged along with the OPAL-RT data to observe the effects.

3.4.5 Unintentional Islanding – Internal

Description: The purpose of this test group is to validate the controller ability to properly shutdown resources based on fault conditions within the microgrid.

Table 3.14 Unintentional islanding - internal test procedures

Initialization Steps	Run initialization script with test variation inputs
Test Variations	(A6, D4)
Triggers	Internal Fault will cause the PCC to trip based on conditions such as fault currents, over voltage, under voltage, over frequency, and under frequency
Actions	Microgrid controller shuts down the system if the fault is permanent.
Expected States	Equipment should be dispatched according to dispatch schedule or shutdown
Time Resolution	100 microsecond simulation and DER control modeling 200 microsecond OPAL-RT data logging 500 millisecond MMC data capture
Metrics	Dynamic stability Loads not being served Min / max of available generation for critical load in microgrid
Data Collected	Transition times from the simulator PCC frequency and voltage Customer load PCC import / export CHP generation during test PV generation during test BESS generation during test
Pass / Fail	Controller transitions to islanded mode or shuts down the system Controller verifies protection settings Load shedding and modulation reduction is appropriate given generation capability and forecasts

Table 3.14 (continued)

Post Processing	The data captured by OPAL-RT will be reviewed to evaluate the transitions during the time of islanding based on internal fault. The generation output will be captured from the controller prior to the islanding and after. During the islanding event the controller changes will be logged along with the OPAL-RT data to observe the effects.

Chapter IV. Implementation of Test Environment

4.1 Overview

A detailed description of implementation of test environment are discussed in this chapter, which tries to resolve the issues listed below:

(1) How to integrate microgrid control system with the testbed so that the controller can take over microgrid operation and make decisions based on system states?

(2) What method to record the data and what approaches to analyze the data?

(3) What would be a reasonable testing procedure for the execution of the tests?

(4) What are other kinds of functionalities we need to add for test execution? Is it possible to automate the testing process since there are a large number of tests, some of which are even long duration?

The diagram of test environment is shown in Figure 4.1. Controller integration approach is illustrated in Section 4.2 and DNP3 communication protocol is discussed in this section. Section 4.3 provides discussion on data logging and post processing analysis. Section 4.4 focuses on automation approach, including the implementation of TestDrive console interface. A test procedure is explained in Section 4.5 and an updated LabVIEW test master is shown in Section 4.6.

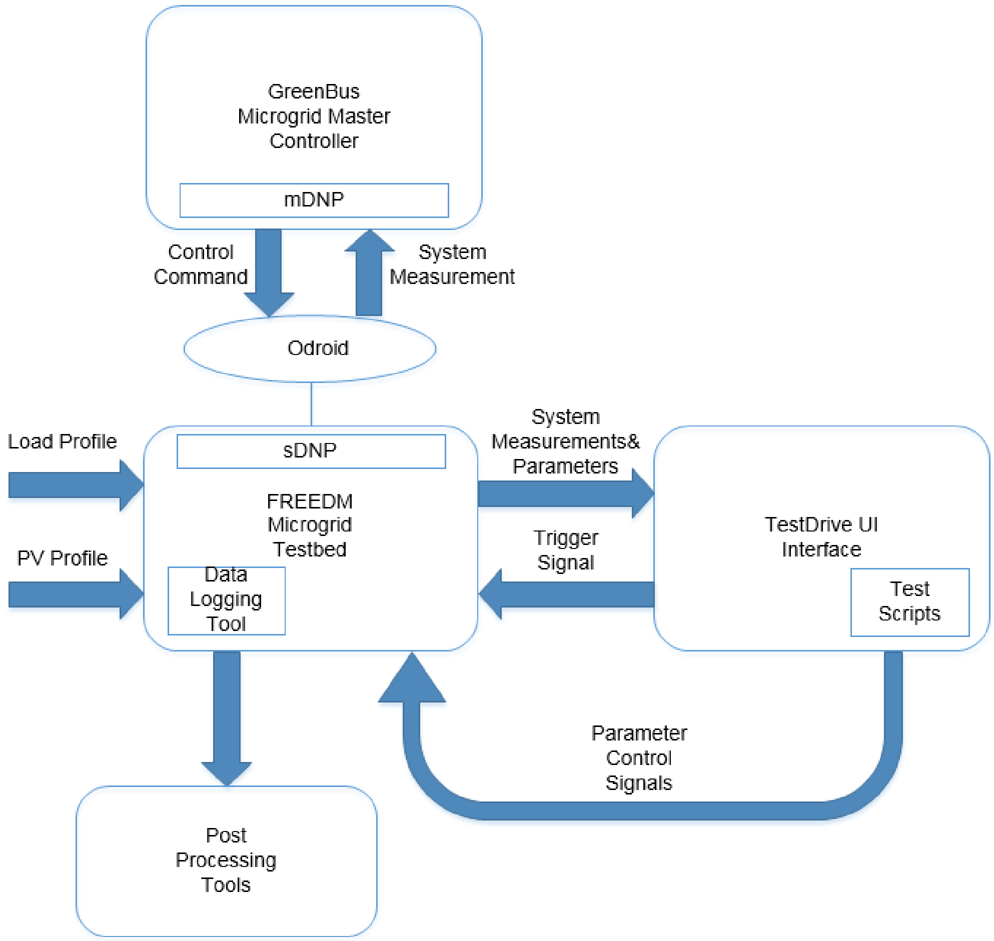


Figure 4.1 Test environment diagram

4.2 Test Integration Approach

4.2.1 DNP3 Slave Interface

DNP3, is one of the dominant Master/Slave communication protocols in North American electric utility SCADA system, and also widely used in other fields such as oil & gas, water and sewage utilities [27]. The reason why DNP3 is gaining such level of popularity in the utility application is not only does it provide interoperability among equipment from different vendors, but also it supports high integrity bi-directional communication with a variety of data types (i.e. timestamps, counter points, etc.) and services (i.e. report by exception, event reporting, etc.).

To emulate utility communication in the field, DNP3 is selected as the protocol in our case to integrate microgrid controller. Figure 4.2 shows the master-slave configuration in our testing environment. The microgrid controller acts as DNP3 master, polling information from real time microgrid testbed as well as sending control commands. The testbed acts as DNP3 outstation (or slave), receiving control commands and providing system states. Either master or outstation should have its own DNP3 interface to support the communication.

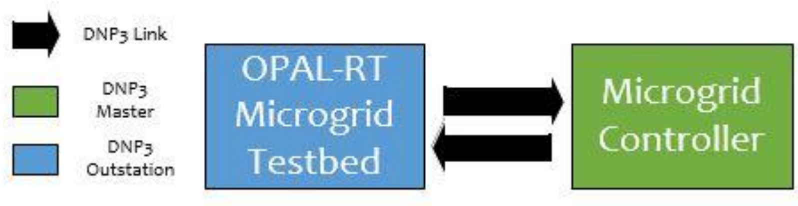


Figure 4.2 DNP3 master-slave configuration

There are four types of data transfer when a test is being executed:

1. System states such as voltages and frequency, or calculated performance metrics such as efficiency and CO2 emission, are polled from outstation to master as analog inputs (AI);

2. Binary status such as the on/off status of CHP and the heat/cool mode of absorption chiller are polled from outstation to master as binary inputs (BI);

3. Control commands, such as CHP output setpoint and BESS discharge target, are sent from master to outstation as analog output (AO);

4. Binary control, used for tripping/closing switches or enabling/disabling resources, are sent from master to outstation as binary output (BO), also commonly referred to as Control Relay Output Block (CROB).

Reference [28] includes a detailed discussion on how to implement DNP3 slave interface in OPAL-RT testbed, but due to the limitation of its model, the author only provides the method for interfacing single microgrid zone. This section focuses on the implementation of multiple slave interfaces for multiple microgrid zones since there are ancillary services tests running on multiple-zone models. During the four-zone tests, each microgrid zone acts as a standalone slave with its own OPAL-RT DNP3 slave interface and communicates with microgrid master controller. Test architecture diagram is shown in Figure 4.3 below.

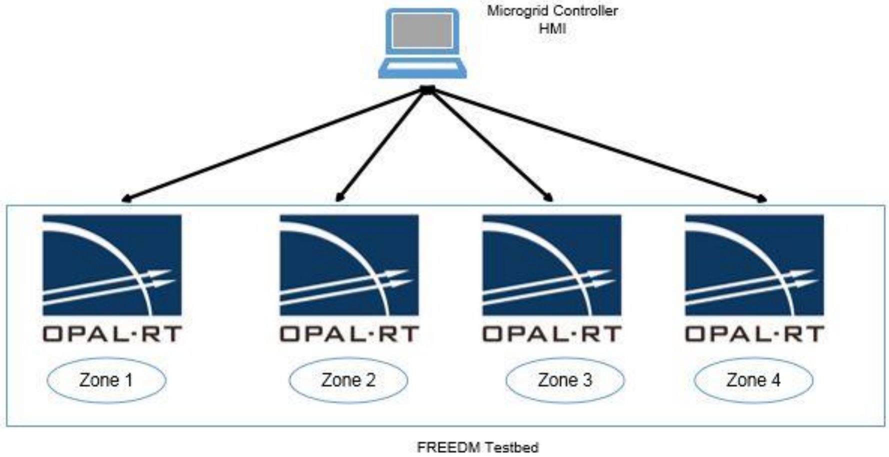


Figure 4.3 Test architecture diagram

To set up the OPAL-RT DNP3 interfaces, we need to configure the module using a XML configuration file that contains all of the parameter required to simulate a DNP3 slave device. Figure 4.4 shows an example of a XML configuration file for multiple DNP3 outstations. If another DNP3 slave device needs to be simulated, the configuration for that specific device can be directly appended to the previous configuration, with a different set of parameters regarding device ID, local IP address, local link address and input-output configuration.

AsyncDNP3_Slave_cfg.xml - Notepad

File Edit Format View Help


```
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<dev_function>Outstation</dev_function>
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<nic_name>eth4</nic_name>
<local_ip>10.76.56.66</local_ip>
<tcp_port>7200</tcp_port>
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<analog_in_max_event_nbr>10000</analog_in_max_event_nbr>
<analog_in_scan_period_ms>100</analog_in_scan_period_ms>
```


Figure 4.4 Example of the configuration file for multiple slave devices

4.2.2 DNP3 Point List

From the perspective of microgrid controller, one important thing to consider is which variables to control and which measurements to observe. Once they are decided, then the testbed should provide these SCADA points to the controller through DNP3 interface. Below is the description of considerations on DNP3 points for different microgrid components:

NG-CHP: Measurements like terminal voltage/frequency, output current, output real/reactive power need to be available since they are all critical operation states. Some thermal characteristics like inlet air temperature, waste temperature and fuel use are also important for tracking efficiency and thermal loading. Besides, NG-CHP units should be under control to start/stop, change mode and enable/disable ABS, and provide controller with output power setpoint and power factor setpoint.

BESS: Measurements like terminal voltage, charging/discharging rate and SOC need to be available since they are all critical states. Besides, BESS should provide control of charging/discharging rate and operation mode (Voltage/Current Source).

PV: Measurements like terminal voltage, output real/reactive power need to be available since they are all critical operation states. Besides, PV should be under control to be enabled/disabled.

Load Group: Measurements like terminal voltage, output current, output real/reactive power, need to be available since they are all critical states. Besides, based on load criticality, some load group should be under control to be shed or modulated.

Point of Common Coupling: Measurements like PCC voltage, PCC frequency, PCC power factor, PCC current and PCC power flow need to be available since they are all critical system states. Besides, PCC breakers should be under control to be tripped/closed.

Overall System: System-level measurements like total DER generation or total load consumption need to be available since they are critical system states.

A DNP3 point list for each microgrid zone is shown in Appendix F.

4.3 Data Gathering and Post Processing Analysis

Data logging functionality is implemented using the block OpWriteFile from RT-LAB library. The block and its parameter setting are shown in Figure 4.5. It works similar to the Simulink ToFile and it is used to record signals and write them in MATLAB files (.mat). Each OpWriteFile block corresponds with one specific acquisition group, which refers to all the signals going through this block. One block is able to record 1000 signals at a time without data loss. Regarding the format of its output files, the first row is simulation time and the second row is the first element of the input vector signal and so on so forth.

The data logging rate of the block is variable and the maximum rate can be as fast as simulation time step. In our case, we use 200 microsecond resolution for recording time-sensitive transient events and 1 second resolution for recording steady-state operation measurements. It's worth noting that we use OpWriteFile block with another RT-LAB block OpTrigger to control the start and stop of writing to the file considering that some of the activities need to be recorded for a short time interval.

Figure 4.6 represents the post-processing workflow for data analysis and documentation. We use MATLAB to get access to the raw data and to calculate the main performance metrics like reliability, system efficiency and emissions since the raw measurements are stored in .mat format. MS Excel is used to store and analyze the most relevant data for the convenience of documentation. It can be raw data like CHP dispatch value and BESS dispatch value, or intermediate results like total energy input, or final results, such as high level performance metrics. R statistical package might be alternative for statistical computing and graphics. What software to use for plotting is on a case-by-case basis, depending on whether the raw data or intermediate results are preferred to generate plots.

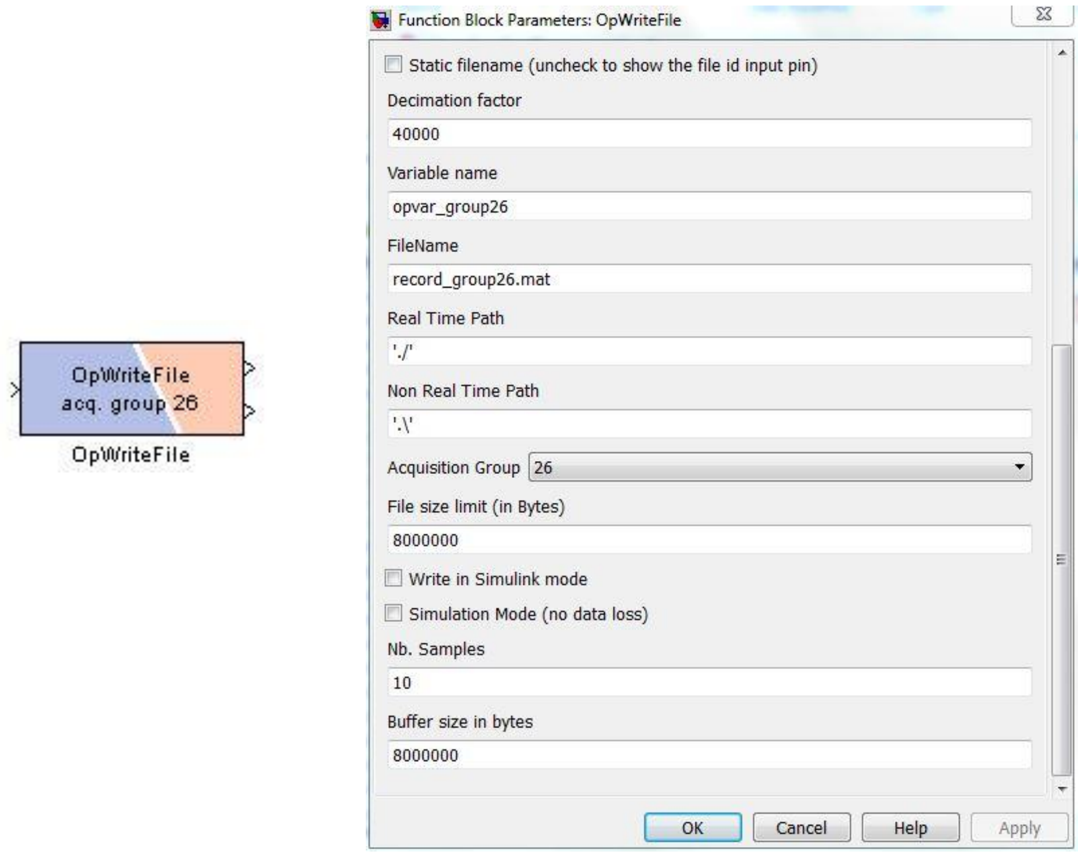


Figure 4.5 OpWriteFile block

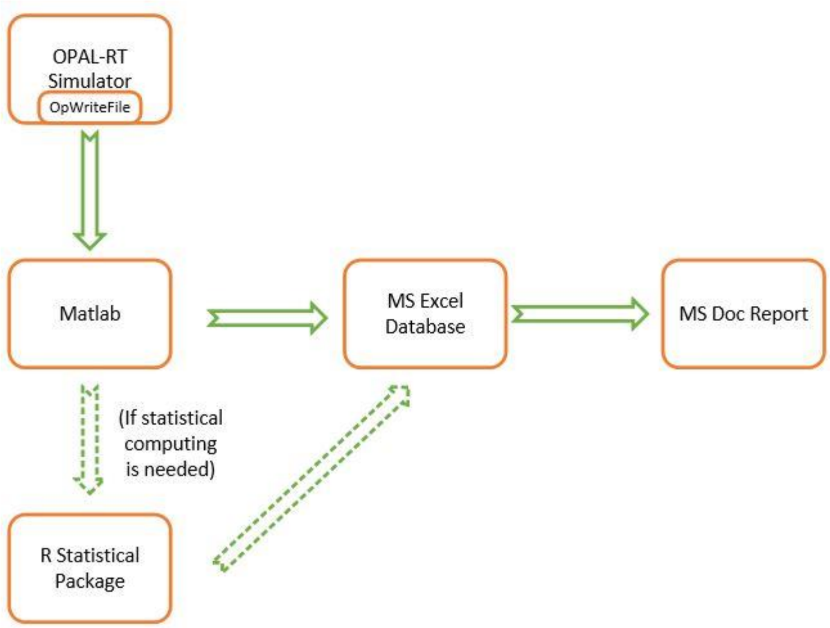


Figure 4.6 Post-processing workflow

4.4 Test Automation

As illustrated in Chapter 3, the testing contains a huge number of sub-tests considering different test variations. The whole process will be time-consuming unless some automation techniques are applied in our testbed.

The TestDrive Interface, developed by Opal-RT Technologies Inc., is the application software used to operate the simulation. It offers us the ability of testing automation as well as data acquisition and parameter control. Several features are listed below about this software:

1) Its signal tree, shown in Figure 4.7, enables easy access to signals and parameters in the model. Therefore, any signals can be displayed and any parameters can be modified during the real time simulation;

2) Its application panes contain indicators and controls to interact with the simulation. Besides, the TestDrive allows users to customize the pane based on the specific task being performed;

3) Its tools used to run the simulator can be operated either manually or automatically via Python scripts.

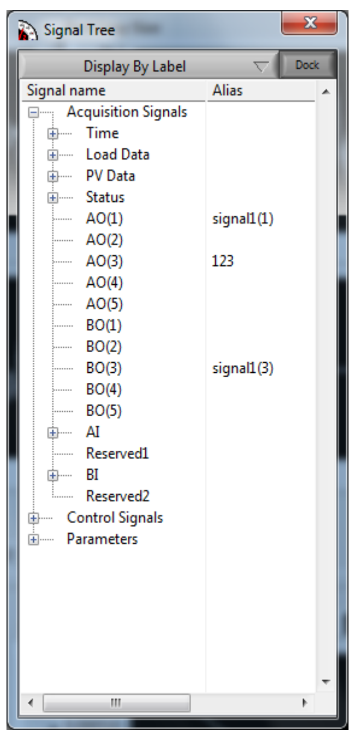


Figure 4.7 TestDrive signal tree

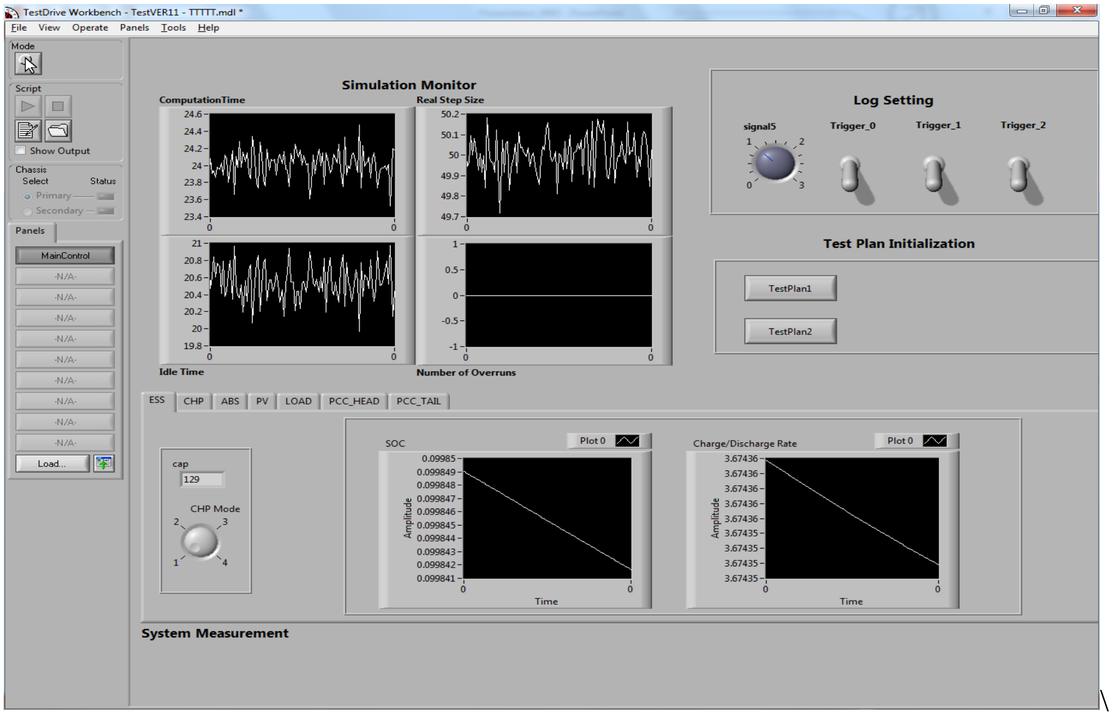


Figure 4.8 TestDrive console interface

Figure 4.8 shows our customized pane used in the testing. On the top left of the pane, four monitors are used to reflect simulation timing information about the model: computation time, real step size, idle time and number of overruns, respectively. The bottom of the pane contain monitors which indicate system states from the microgrid model. All the measurements in the point list are also shown in the TestDrive. Note that these measurements are not acquired through DNP3 communication link but captured by TestDrive itself. On the top right of the pane, two kinds of control clusters are set up for testing purpose. The upper one contains four controls: The most left one is a control that can create a new file for storing data. Three controls on the right, which are used as triggers of data logging process, correspond to three different data-logging rates. The motivation of having multiple logging rates is to capture dynamics more correctly when an event happens. The details of data logging are already discussed in the previous section. The lower panel controls the execution of several testing scripts that contain parameter initialization, data logging trigger and event trigger. These scripts allow data logging and events to be triggered automatically at any time instead of manually by testers. Once the scripts are running, the following work are handled by the scripts and testers are free to leave until the simulation needs to be stopped.

4.5 Test Execution

In support of a variety of tests, meeting the following requirements is required:

1) The tester can select a day and start time for the microgrid controller. The year of the date are 2014 based on the load information from local utility.

2) The tester can manually coordinate the simulation start with microgrid controller based on the same start day and time.

3) The tester can set the initial conditions for the simulation and microgrid controller.

A workflow of test execution is shown as Figure 4.9. In the pre-test phase, both microgrid controller and testbed should be correctly configured using pre-defined initial parameters. After the simulation is up and microgrid controller is running, a regular-speed data logging function are triggered to record system states and then test scripts will be started where all the events are defined as well as the corresponding high-speed data logging triggers. During the phase of post-test, the original database will be loaded into MATLAB (or R) where all the performance metrics are calculated and analyzed.

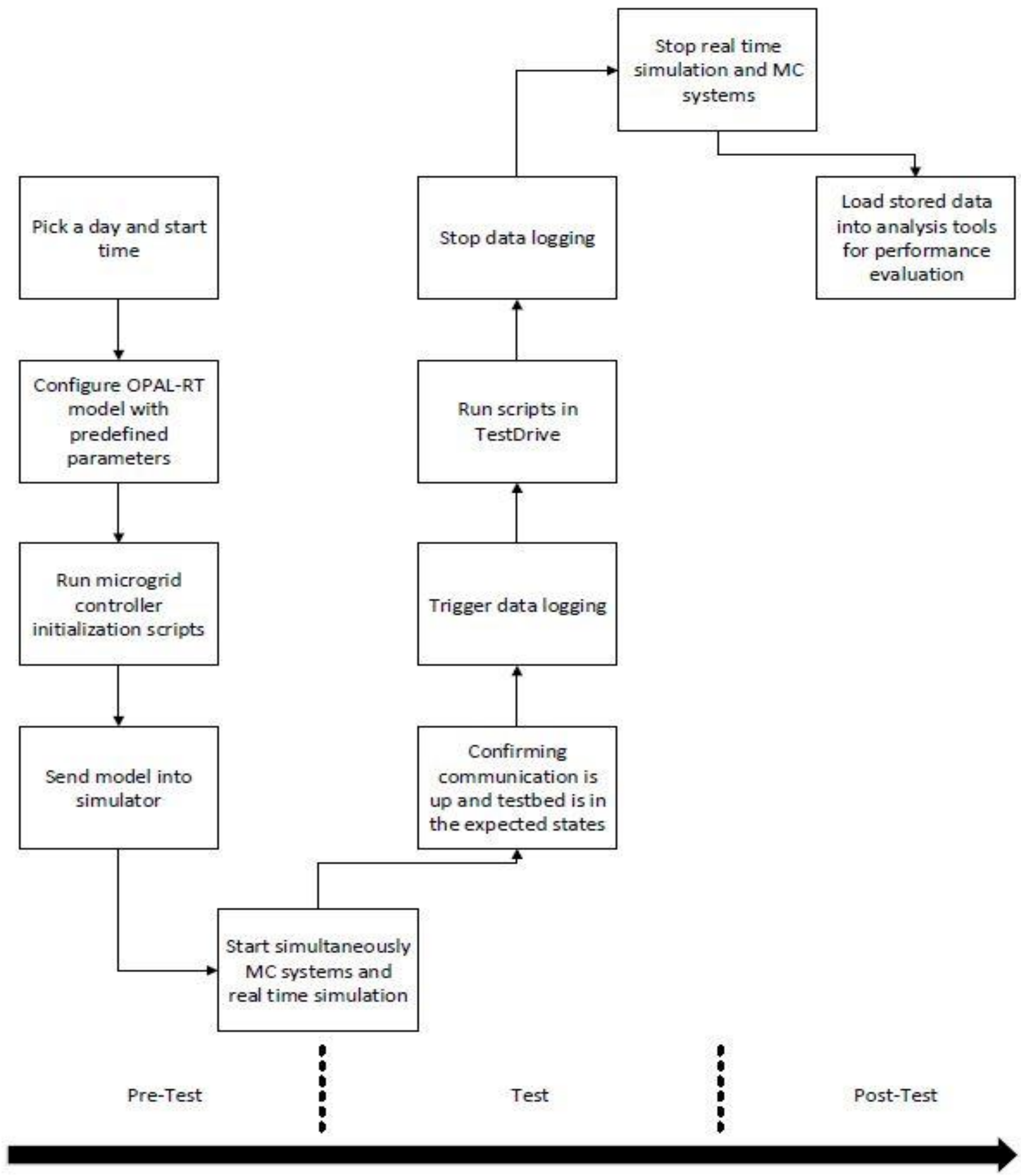


Figure 4.9 Testing workflow

4.6 Test Master

A DNP3 master station is redesigned in LabVIEW as an alternative testing master to provide more flexibility in conducting tests, considering the condition that the tested controller could be offline sometimes due to maintenance or malfunction.

Compared to the test master in [28], more functions are introduced to this testing master with a nicer graphic interface. Figure 4.10 shows the user interface of the master. The one-line diagram is integrated to give a more straightforward representation of system topology. Instead of using tab control, components are represented directly using sub panels. By clicking the component button, users can open the corresponding sub panels and see the states of the components. In addition, the testing master is able to send out control commands automatically instead of manually. It allows testers to put some predefined dispatch pattern of CHP and BESS for evaluating steady-state operations.

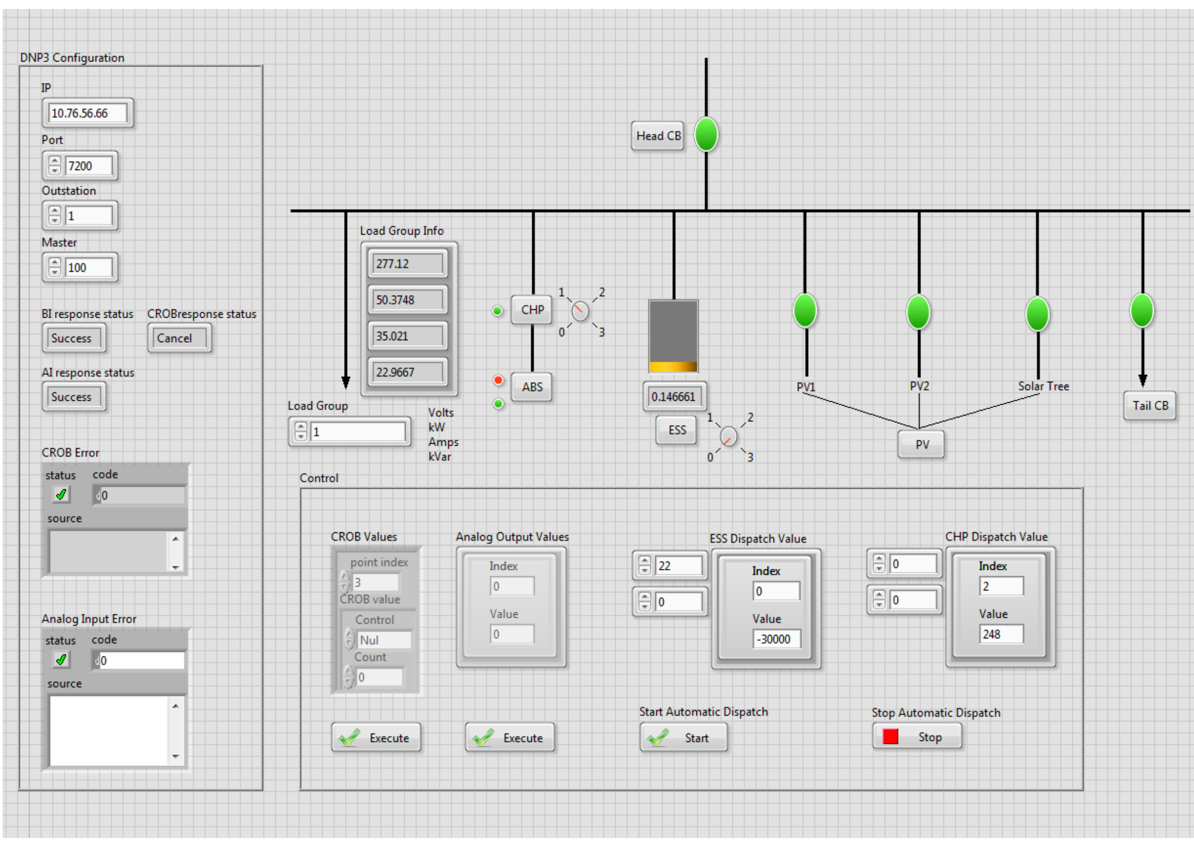


Figure 4.10 LabVIEW test master

Chapter V. Test Result Analysis

The tests are run on the microgrid Zone 1 testbed. The system parameters including load profiles and resources configuration are presented in Chapter 2, Appendix A and Appendix B. Energy management – grid connected use case is considered in this chapter to evaluate the performance of microgrid controller. For the use case, testing scenarios are illustrated and the post-processing analysis is performed from different aspects.

5.1 Energy Dispatch – Grid Connected

When the microgrid operates in grid-connected mode, the microgrid controller must generate a dispatch schedule that optimizes cost, efficiency and emission using load forecast and renewables forecast. Since microgrid controller is not available for the time being, the developed LabVIEW master is applied as an alternative to put our own patterns of CHP and BESS dispatch for evaluation purposes.

As is shown in Figure 5.1, a dispatch schedule of CHP and BESS is predefined. The CHP runs at its maximum capacity of 248 kW the whole day. The BESS is discharged and charged nine times over the day. Most of the cycles happen during the night and only a few cycles occurs in the daytime.

Figure 5.2 (a) shows the dispatch for electricity on a summer peak day. It can be seen that the CHP unit serves the majority of the base load, and the remaining consumption is mainly supplied firstly by the grid, then by the PV and finally by the grid, over a 24 hour period. It is worth noting that the load profile increases during the daytime and falls off in the late afternoon so it is matched well by the PV output. Due to self-generation within microgrid area, the energy from the main grid decreases substantially (Figure 5.2 (b)).

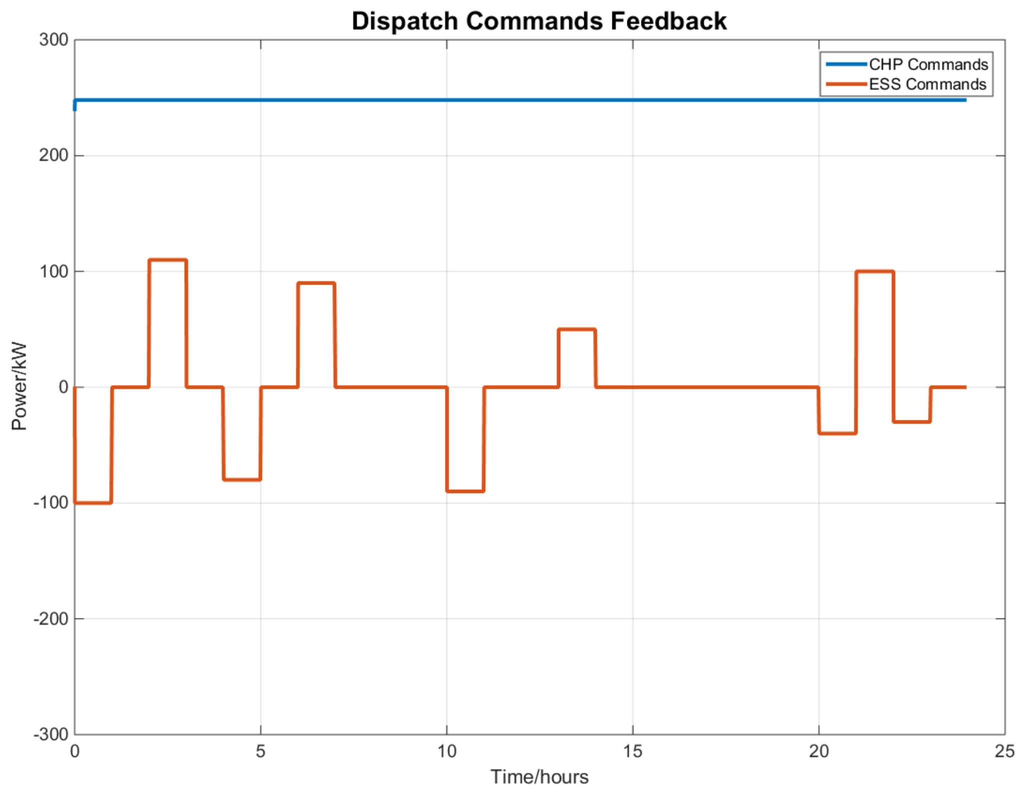
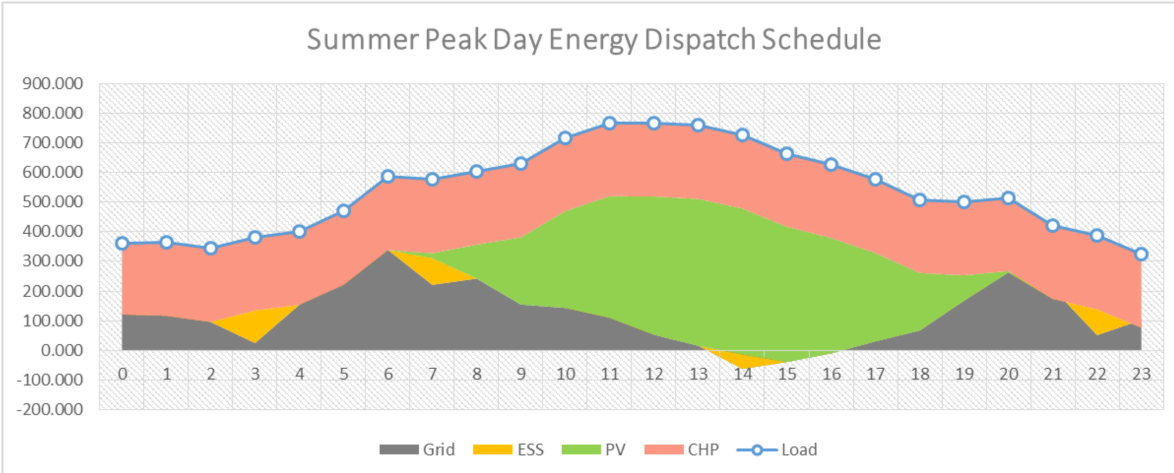
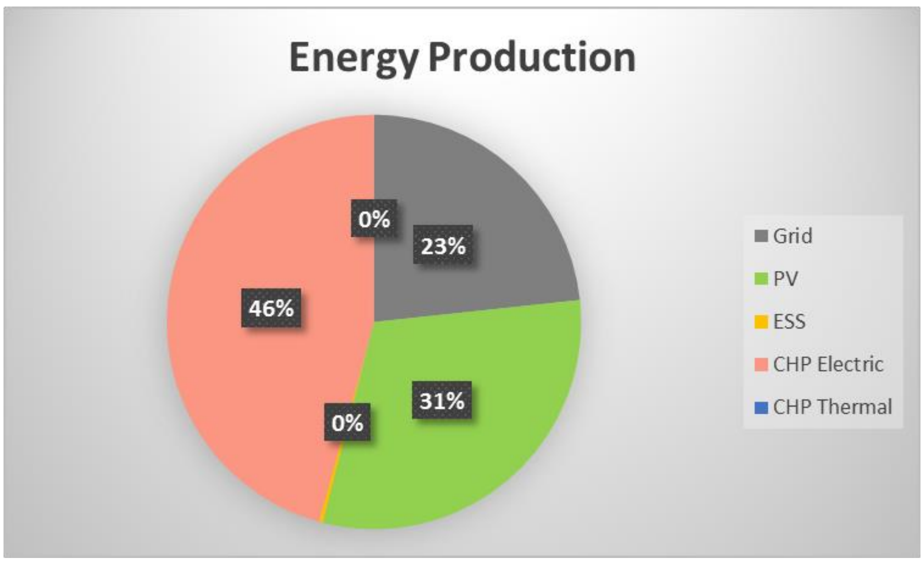


Figure 5.1 Predefined dispatch schedule of CHP and BESS from LabVIEW master



(a)



(b)

Figure 5.2 (a) Electricity dispatch (b) Energy production

The performance metrics of microgrid and base case are depicted in Figure 5.3 in terms of system efficiency and GHG emissions. The details about performance metrics are shown on Table 5.1. It shows that microgrid implementation brings down total emission from 7238 kg to below 5000 kg on a daily basis as well as average emission factor from 0.504 kg/kWh to 0.329 kg/kWh. Regarding the emission requirements, the results indicate that the microgrid meets the target of 0.40 kg/kWh. This has to do with the fact that more electricity is generated by carbon-free PV panels and low emission CHP unit. However, the microgrid efficiency stays almost the same (strictly a little worse than) as the grid without DERs. The reason why the scenario doesn't prove the improvement of the efficiency is that the heating and cooling load sinks are not taken into account in the simulation. Without considering the CHP contribution to supplying thermal loads, the CHP unit is operated based on the fuel efficiency curve shown in Figure 5.4. In the simulation, the ambient temperature is set to be 75.2 degree Fahrenheit, corresponding to a fuel efficiency of around 28%. It implies the CHP runs inefficiently compared with the main grid without considering thermal outputs. It is illustrated by the result that the reuse of exhaust heat for thermal supplies significantly impacts the CHP efficiency, and in turn the grid efficiency.

Table 5.1 Performance metrics for energy dispatch – grid connected

	Baseline	Microgrid	Improvement Rate
Efficiency	0.400	0.389	-0.028
Total Emission	7238.024	4739.636	0.345
Average Emission Factor	0.504	0.329	0.348

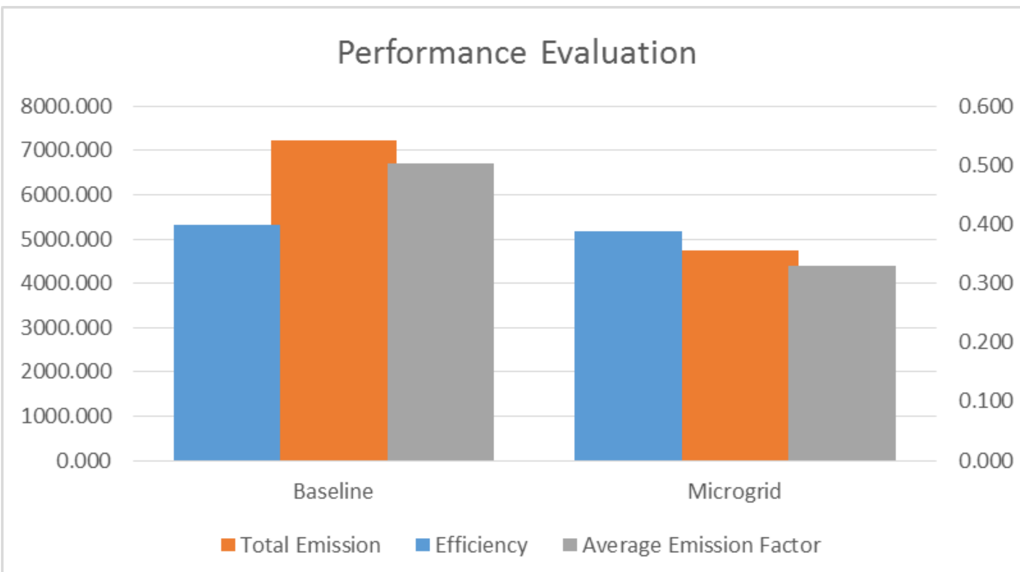


Figure 5.3 Evaluation of baseline (no DERs) vs microgrid

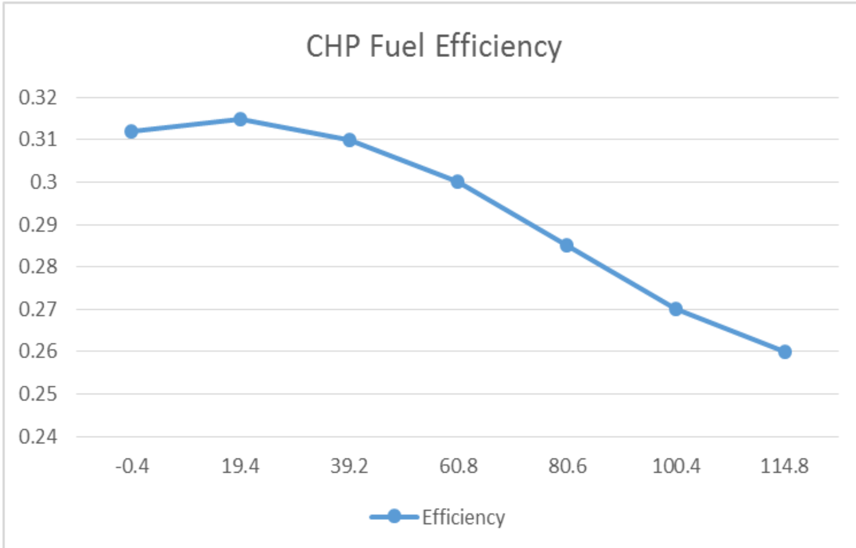
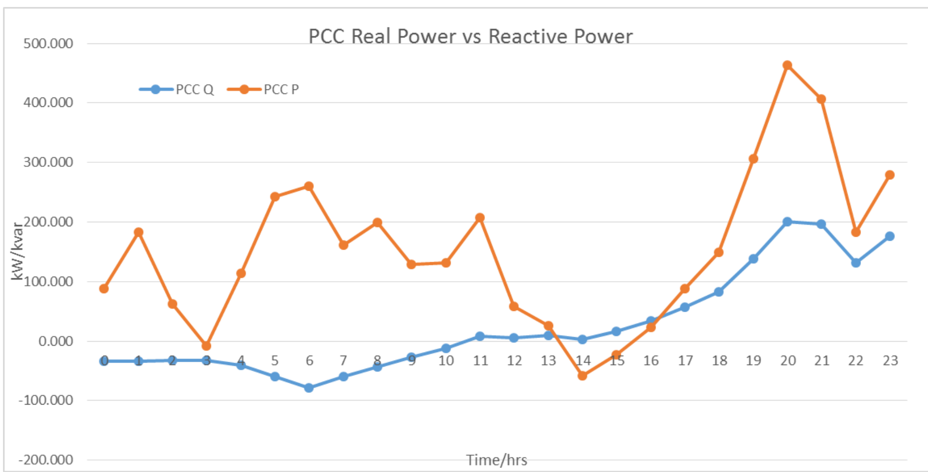
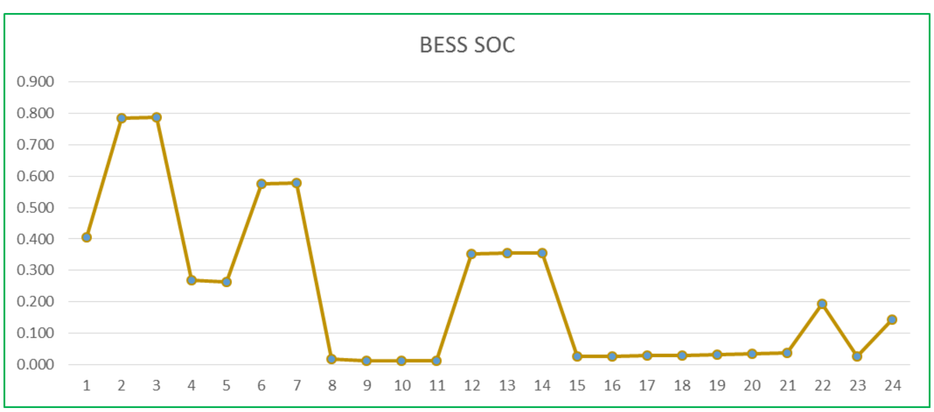


Figure 5.4 CHP fuel efficiency vs temperature



(a)



(b)

Figure 5.5 (a) PCC real/reactive power over a 24 hour period (b) BESS SOC over a 24 hour period

Figure 5.5 (a) shows that, during the grid-connected operation of the microgrid, the real power of the PCC, shown in an orange marked line, ranges from -60 kW to 480 kW, while reactive power supplied by the grid is within a tighter bound from -80 kvar to 200 kvar. However, utility usually expects a smaller peak of real and reactive power from the microgrid since high loading of microgrid can cause further infrastructure investment. Also a less fluctuating real power at PCC is expected than what is shown in Figure 5.5 (a). Figure 5.5 (b) shows how BESS State of Charge changes over time. It's worth noting that the SOC, represented in an dark yellow marked line, shows that BESS is in deep discharge in both the morning and the afternoon. For some types of battery, battery life can be shorten if it is usually used in a deep cycle application. Situations like BESS deep discharge and large real/reactive power imports will be avoided by a more sophisticated management strategy rather than a predefined dispatch pattern. Although how to develop the strategy is beyond the scope of the thesis, we can see that PCC real/reactive power and BESS SOC could be valuable metrics to evaluate how well the microgrid controller are managing the system.

Chapter VI. Conclusion and Future Work

The thesis work focuses on test protocols design, test environment implementation and post processing test analysis for the purpose of evaluating commercial microgrid controller. The microgrid testbed is discussed, including details on system modeling and validation. Then evaluation methodology is formulated and test protocols are introduced. The details of test environment implementation are provided to demonstrate our testbed has the full functionality for controller integration, test execution and performance evaluation. The test results show the effectiveness of our microgrid testbed as a testing platform for validating different use cases of microgrid controller.

The contributions and conclusions of the thesis are summarized as follows:

- Developed a reduced four-zone microgrid system model that allows multi-microgrid tests based on utility field database;
- Proposed evaluation methodology for microgrid controller with respect to emission, efficiency and reliability metrics;
- Designed test protocols for some of the use cases;
- Established a complete multi-slave DNP3 setup for four-zone microgrid testbed;
- Implemented and improved test environment, including TestDrive console interface, data recording and LabVIEW test master;
- Validated microgrid testbed functionality and evaluation methodology by running energy dispatch – grid connected case.

There are still a lot of work to be done to finalize the microgrid testbed. From the modeling perspective:

- Load groups are all modeled as constant power load, which is not fully representative of load types in the real world. Constant impedance load and constant current load are to be included with some weight factors. Also thermal loads and motor loads need to be added to the model.
- Instead of average emission factor, it would be more realistic to have CHP emissions modeled as a function of loading condition and temperature.

From the testing perspective:

- Although we have discussion on how to compute relevant metrics from one test, it remains to be figured out how to reasonably extrapolate performance for the entire year based on the results from discrete tests.

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APPENDICES

Appendix A

This appendix includes the list of criticality for the entire load group within microgrid boundaries, shown in Table 1.

Table 1. List of criticality of load groups

Customer Name	Microgrid Zone #	Criticality
Group 1	1	H
Group 2	1	H
Group 3	1	H
Group 4	1	H
Group 5	1	M/L
Group 6	1	O
Group 7	1	O
Group 8	1	O
Group 9	1	O
Group 10	1	O
Group 11	2	H
Group 12	2	L
Group 13	2	L
Group 14	2	M
Group 15	2	M
Group 16	2	O
Group 17	2	O
Group 18	2	O
Group 19	2	O
Group 20	3	H/L
Group 21	5	H
Group 22	5	H
Group 23	5	H
Group 24	5	H
Group 25	5	L
Group 26	5	M
Group 27	5	O

Appendix B

The appendix contains microgrid system topologies, shown from Figure 1 to Figure 7.

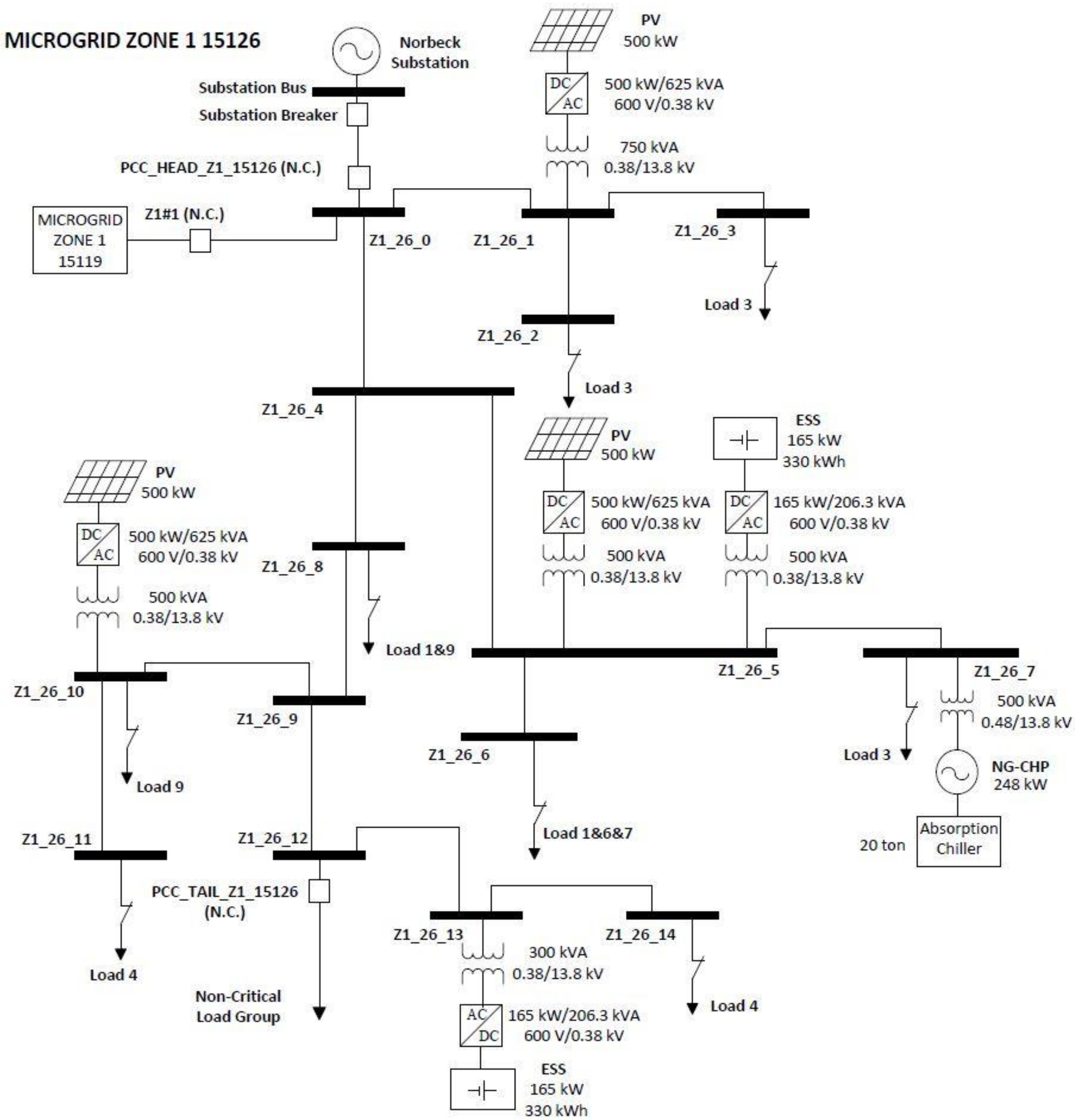

Figure 1. One-Line Diagram of Zone 1 (Feeder 15126)

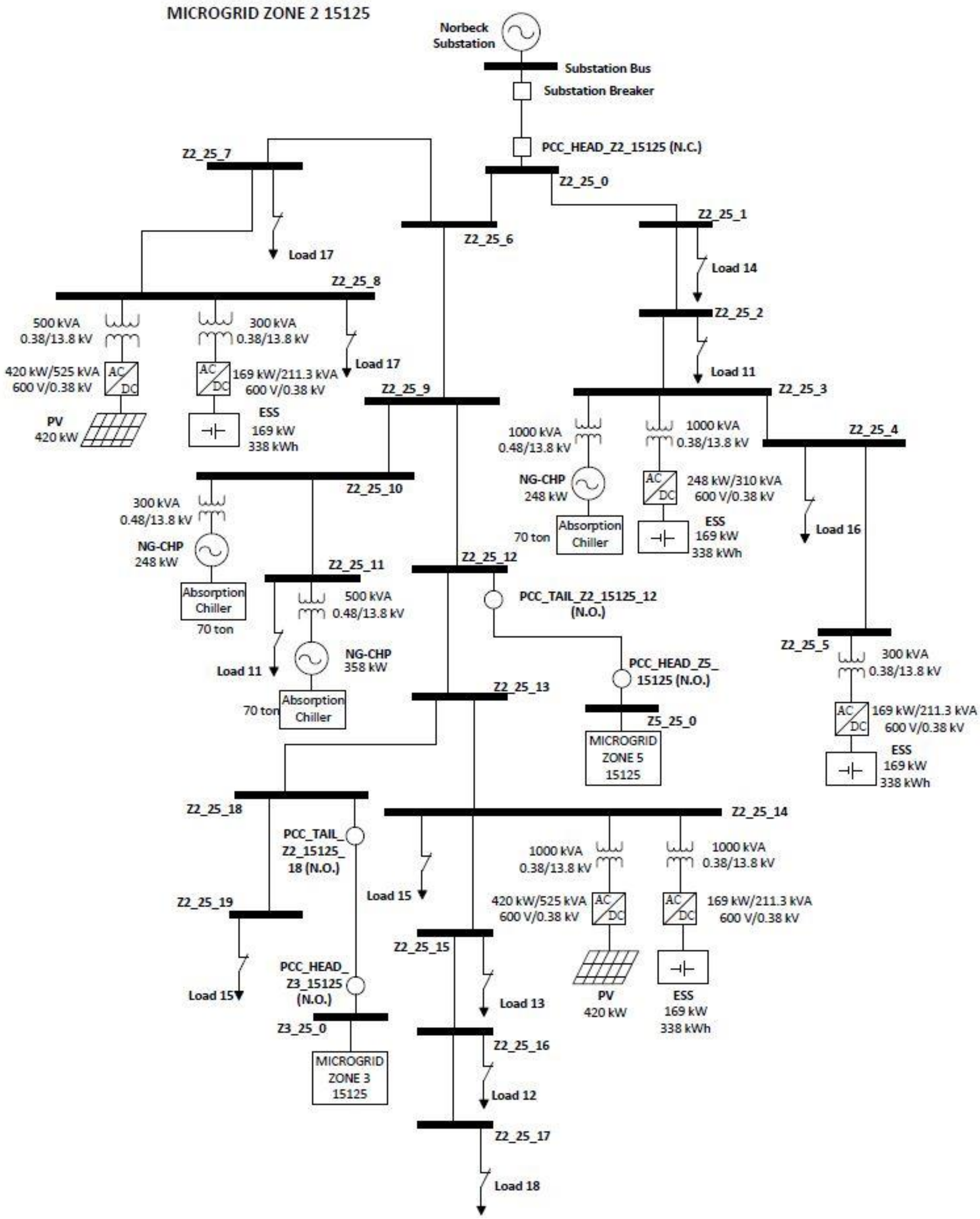

Figure 2. One-Line Diagram of Zone 2 (Feeder 15125)

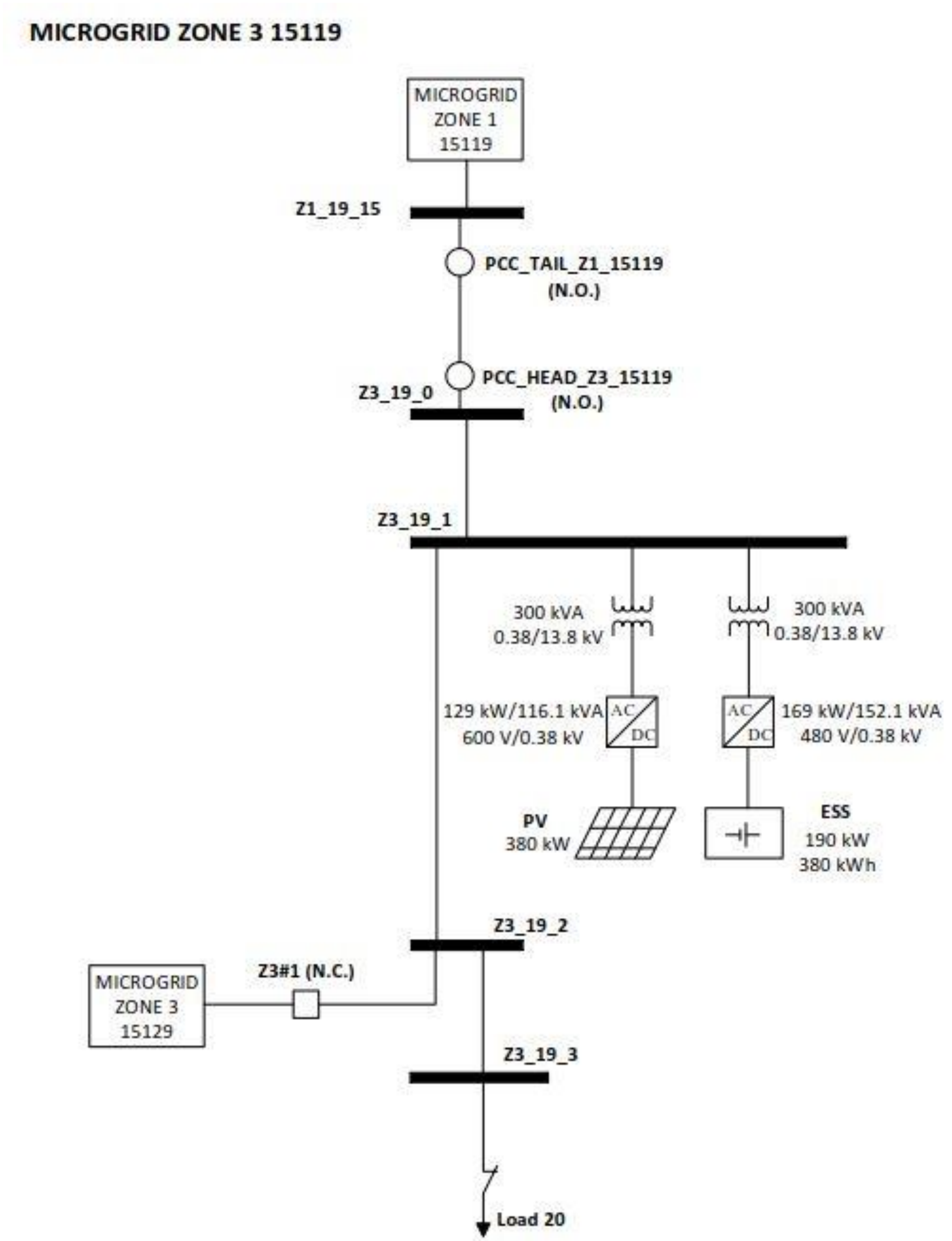

Figure 3. One-Line Diagram of Zone 3 (Feeder 15119)

MICROGRID ZONE 3 15125

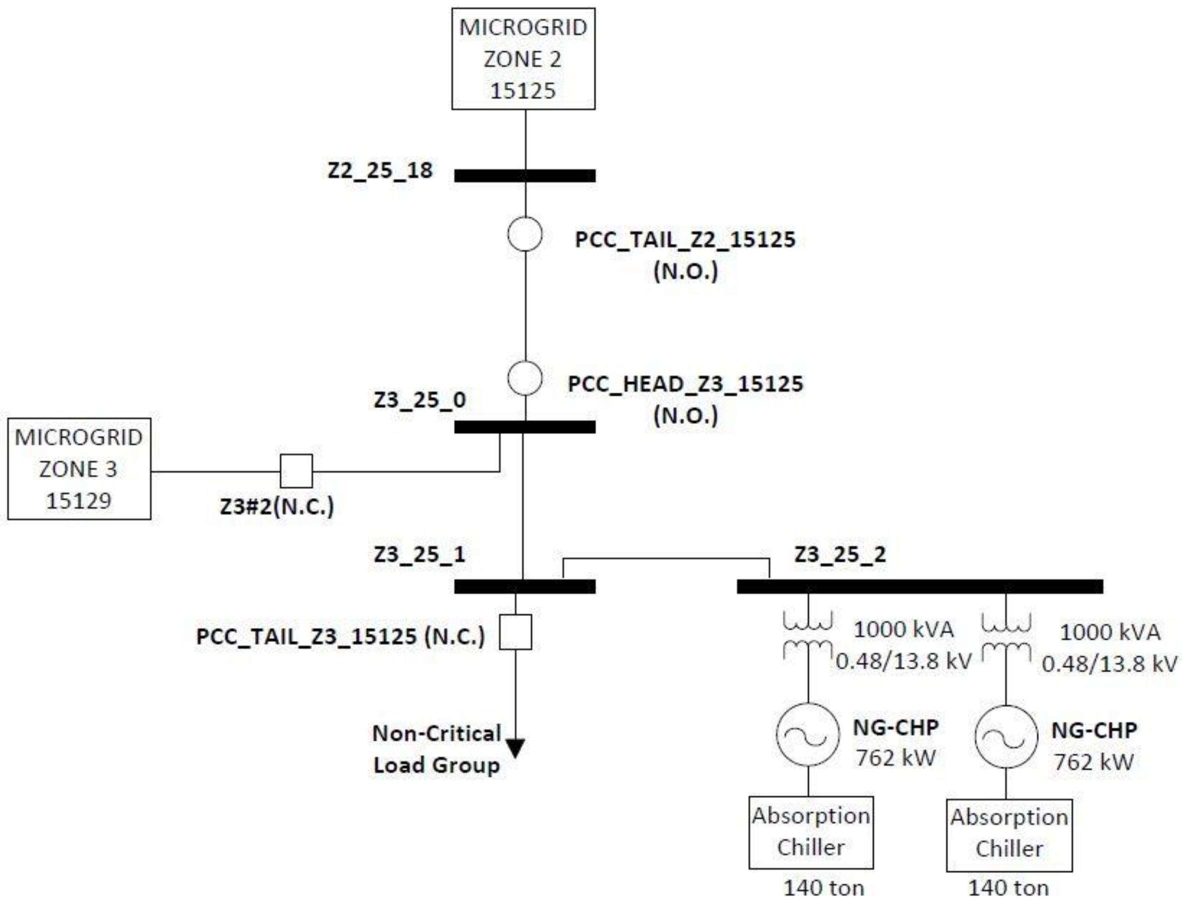

Figure 4. One-Line Diagram of Zone 3 (Feeder 15125)

MICROGRID ZONE 3 15129

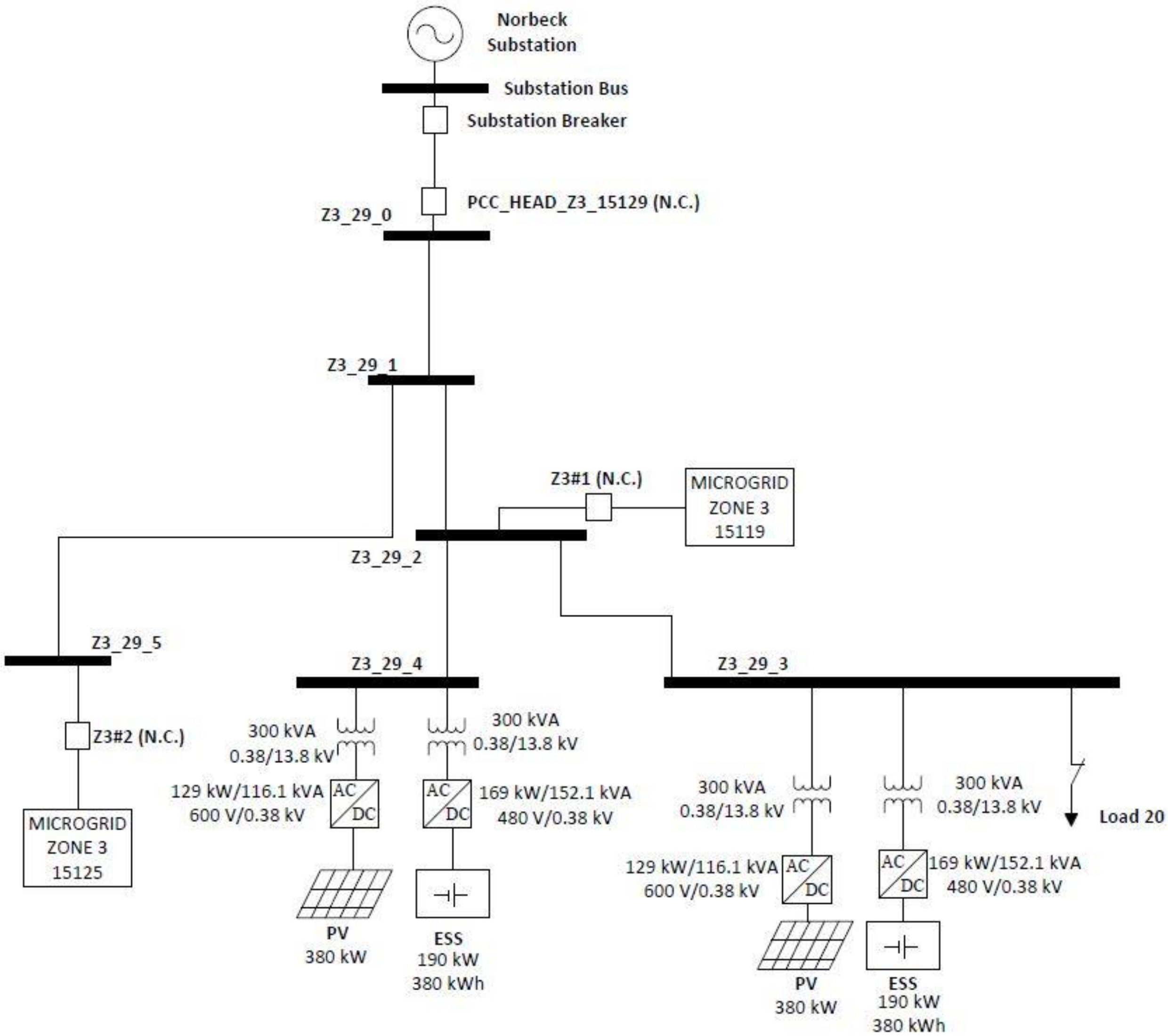

Figure 5. One-Line Diagram of Zone 3 (Feeder 15129)

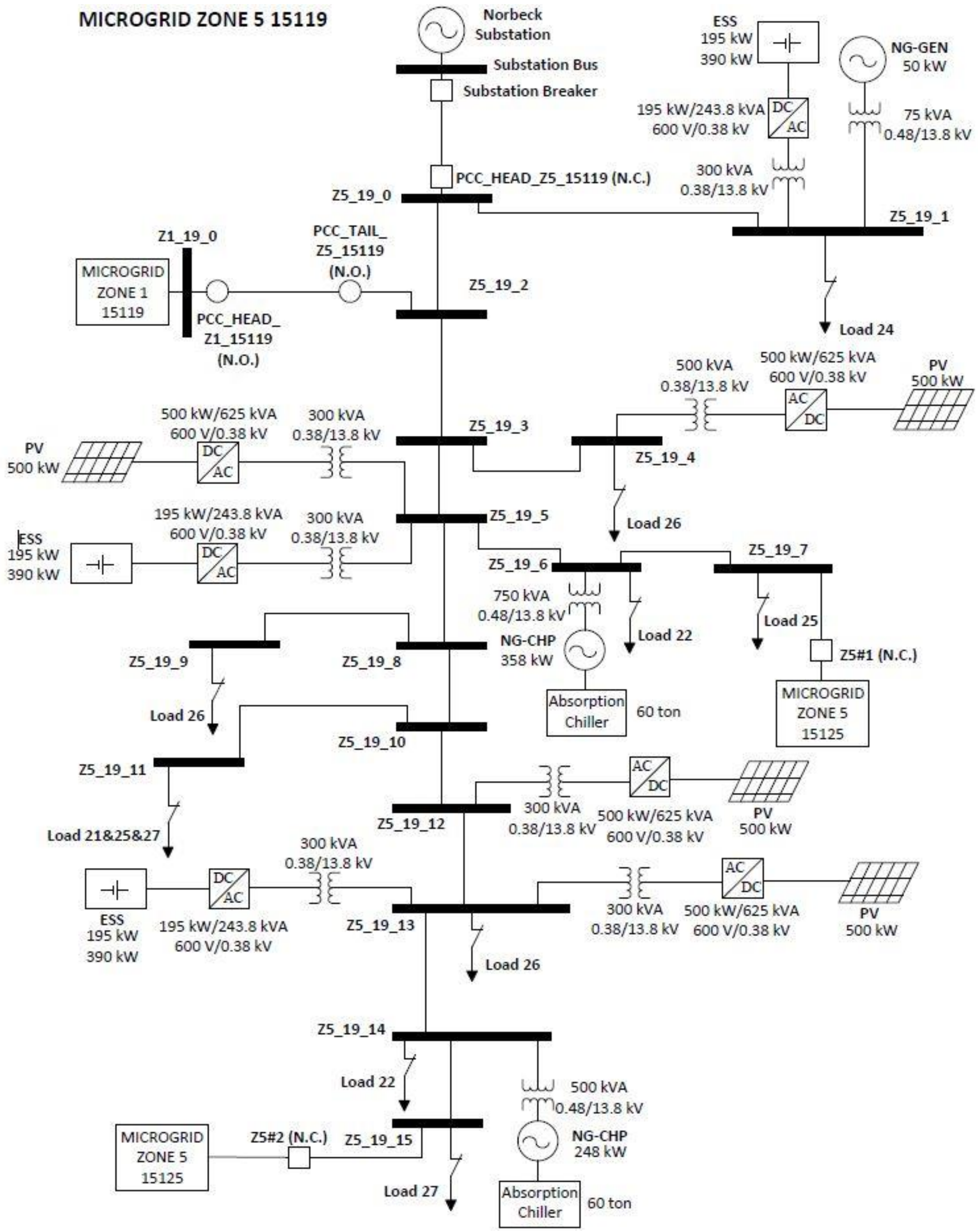

Figure 6. One-Line Diagram of Zone 5 (Feeder 15119)

MICROGRID ZONE 5 15125

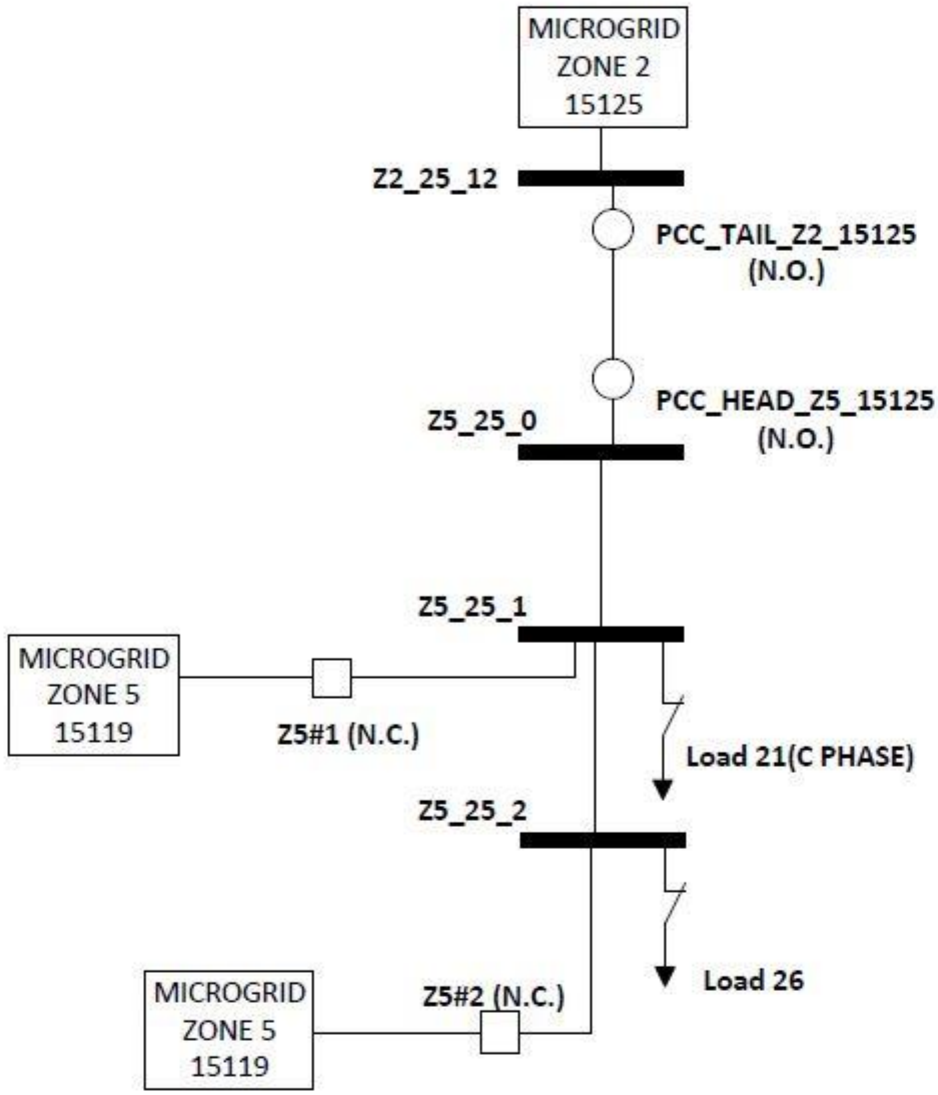

Figure 7. One-Line Diagram of Zone 5 (Feeder 15125)

Appendix C

This appendix includes the use case definition in Olney microgrid project. It mainly refers to EPRI ORNL use cases.

Energy management: The EPRI use case takes a traditional energy management approach – economic dispatch, short-term dispatch, optimal power flow, and other processes typical in utility control room environments. The MMC will have corresponding applications that coordinate among multiple DERs, load assets, energy storage system and main grid. Within that portfolio, the system will optimize the microgrid based on load/renewable forecast, ancillary services events, time-of-use pricing, coincident and non-coincident demand charges, changes in configuration, outage of specific equipment, or any other kind of change to determine the optimal use of assets 48 hours ahead. The optimization is based on economics, reliability and CO2 emission reductions.

Ancillary services: The MMC will be able to bid into ancillary service markets and negotiates with a market operator. The MMC also will have the ability to accept DR requests procured by the market operator. This will be implemented by increased generation and/or interruptible load based on the microgrid design. The MMC is capable of being configured to support various market functions and will require detailed analysis in the microgrid design phase to understand the configuration and interfaces needed to support these functions.

Intentional islanding: For each microgrid zone, the islanding process will be initiated by a utility operator or local energy manager. A re-dispatch schedule involving interruptible loads and DERs is computed by MMC so that there is no import/export of real/reactive power at PCC. Where applicable, a utility operator will provide the appropriate permission for opening the PCC. The local MMC for each microgrid zone will be responsible for setting the voltage source and load-following resource.

Unintentional islanding: The MMC will be configured to support the island-to-grid transition, ideally without loss of load. The microgrid design must account for the IEEE 1547 Std.-2008 to support voltage and frequency support in case of grid-side loss of power or PCC tripping. The MMC has the capability to optimize system energy resources and modulate load for stable operation.

Island-to-grid connected transition: As with intentional islanding, the utility operator where applicable will provide the appropriate permission to close the PCC. The local MMC will initiate resynchronization by sending control commands to the sources and loads so that differences between microgrid voltage and AEPS voltage meet specified criteria at the PCC.

Black start: The local MMC will provide a workflow process for restarting the system. Each microgrid zone will have a unique sequence of operations for systematically restarting generation while increasing load to the system. The microgrid design phase will provide the proper sequence of operations for the MMC.

Appendix D

The appendix gives Table 1 that identifies specific day for each day type.

Table 1. Day type identification for testing

Season	**Load Type**	**Variation Type**	**Specific Day**	**Actual Values**
Spring	Peak KW day	A1	5/27/2014	681.5 kW
Spring	Maximum kWh day	A9	5/13/2014	11,636.6 kWh
Spring	Average kWh day	A10	5/1/2014	9,271.2 kWh
Spring	Minimum kWh day	A7	5/4/2014	7,172.1 kWh
Summer	Peak KW day	A2	7/2/2014	758.1 kW
Summer	Maximum kWh day	A11	7/2/1014	13,018.7 kWh
Summer	Average kWh day	A5	7/18/2014	10,555.5 kWh
Summer	Minimum kWh day	A12	7/2/2014	8,083.8 kWh
Fall	Peak KW day	A3	9/2/2014	736.0 kW
Fall	Maximum kWh day	A13	9/2/2014	12,301.5 kWh
Fall	Average kWh day	A14	9/22/2014	9,942.3 kWh
Fall	Minimum kWh day	A8	9/14/2014	7,606.0 kWh
Winter	Peak KW day	A4	12/2/2014	550.5 kW
Winter	Maximum kWh day	A15	12/2/2014	10,360.5 kWh
Winter	Average kWh day	A6	12/24/2014	8,038.3 kWh
Winter	Minimum kWh day	A16	12/25/2014	6,157.2 kWh

Appendix E

The appendix includes test runs summary as well as the approximate duration of the whole test runs In order to extrapolate for the entire year of 2014, the test variations will be run for a period of time (typically 8 to 24 hours). Then the results will be compiled based on distribution of each day-type.

Table 1. Test procedure run summary

Test Categories	Variations	Hours Per Run
Energy Management – Grid Connected	(All day type, Sunny)	24
	(Summer peak kW day, Rainy)	8
	(Summer peak kW day, Component failures)	2
Energy Management – Islanded	(All day type, Sunny)	24
	(Summer peak kW day, Rainy)	8
	(Summer peak kW day, Component failures)	2
	(Winter peak kW day, Large motor startup)	1
	(Winter peak kW day, HVAC loss)	1
Energy Management – Resiliency	(All day type, Sunny)	24
	(Summer peak kW day, Rainy)	8
	(Summer peak kW day, Component failures)	2
	(Winter peak kW day, Large motor startup)	1
	(Winter peak kW day, HVAC loss)	1
Ancillary Services – Demand Response	(All day type, Sunny)	4
Ancillary Services – Power Management	(All day type, Sunny)	2
Intentional Islanding – Grid Operator	(Summer peak kW day, Partial cloudy)	1
	(Summer peak kW day, Partial cloudy, PV trip)	1

Table 1 (continued)

Intentional Islanding - Stability	(Summer average kWh day, Rainy, Component failures)	1
	(Summer average kWh day, Rainy, Large motor startup)	1
	(Summer average kWh day, Rainy, HVAC loss)	1
Unintentional Islanding - External	(Winter average kWh day, Loss of grid supply)	1
	(Summer average kWh day, Frequency dip)	1
	(Summer average kWh day, External fault)	1
	(Summer average kWh day, CHP trip, Frequency dip)	1
	(Summer average kWh day, PV trip, Frequency dip)	1
	(Summer average kWh day, BESS trip, Frequency dip)	1
Unintentional Islanding - Internal	(Winter average kWh day, Internal fault)	1
Island-to-Grid Transition	(Spring min kWh day, Partial cloudy)	1
Microgrid Blackout	(Fall min kWh day, Partial cloudy)	1
Cyber Security – Grid Connected	(Fall min kWh day, Partial cloudy, Communication lost with hosted system)	1

Appendix F

The appendix contains a set of DNP3 points shown in Table 1.

Table 1. DNP3 Point List

Analog Input	ESS1	ChgDischgRate	Charge/Discharge Rate
Analog Input	ESS1	ReactivePowerSetpoint	Feedback for Control
Analog Input	ESS1	SOC	State of Charge
Analog Input	ESS1	Mode	Operation Mode
Analog Input	ESS1	Va	Phase A Voltage
Analog Input	ESS1	Vb	Phase B Voltage
Analog Input	ESS1	Vc	Phase C Voltage
Analog Input	Load1	Voltage	
Analog Input	Load1	Amps	
Analog Input	Load1	kW	
Analog Input	Load1	kvar	
Analog Input	PV1	kW_cap	kW Capacity
Analog Input	PV1	kW_tot	Total kW
Analog Input	PV1	kVAR	Total kVAR
Analog Input	PV1	Mode	PV Operation Mode
Analog Input	PV1	Va	Phase A Voltage
Analog Input	PV1	Vb	Phase B Voltage
Analog Input	PV1	Vc	Phase C Voltage
Analog Input	PCC1_cbr_util	kV	kV
Analog Input	PCC1_cbr_util	Amps	Amps
Analog Input	PCC1_cbr_util	kW	kW
Analog Input	PCC1_cbr_util	Hz	Hertz
Analog Input	PCC1_cbr_util	PwrFact	Power Factor
Analog Input	PCC1_cbr_util	Va	Phase A Voltage
Analog Input	PCC1_cbr_util	Vb	Phase B Voltage
Analog Input	PCC1_cbr_util	Vc	Phase C Voltage
Analog Input	NG_CHP	Capacity	Generator Capacity
Analog Input	NG_CHP	EletricalOutputVoltage	Voltage

Table 1 (continued)

Analog Input	NG_CHP	EletricalOutputCurrent	Current
Analog Input	NG_CHP	EletricalOutputRealPower	Total kW
Analog Input	NG_CHP	EletricalOutputReactivePower	Total kvar
Analog Input	OlneyZone1Microgrid	Mode	Mode of microgrid
Analog Input	OlneyZone1Microgrid	State	State of microgrid
Analog Input	OlneyZone1Microgrid	IslandingPermissive	Islanding Allowed
Analog Input	OlneyZone1Microgrid	Generation	Total Generation
Analog Input	OlneyZone1Microgrid	Load	Total Load
Status	PV1	Status_Ena_Dis	Status of Enable/Disable
Status	PCC1_Head_CBR	Status	Status Open/Close
Status	NG_CHP	Status_Start_Stop	Status of Start/Stop
Setpoint	ESS1	SetRateTarget	Charge Rate Target
Setpoint	ESS1	SetMode	ESS Mode
Setpoint	ESS1	SetReactivePower	Reactive Power Target
Setpoint	NG_CHP	SetOutTarget	Output Target
Setpoint	NG_CHP	SetPowerFactor	
Setpoint	NG_CHP	SetMode	
Control	PV1	Enable/Disable	
Control	PCC1_Head_CBR	Trip/Close	Open Breaker
Control	NG_CHP	Start/Stop	Start Unit