MICROGRID RISK REDUCTION FOR DESIGN
AND VALIDATION TESTING USING
CONTROLLER HARDWARE IN THE LOOP

by

John Kendall Nowocin

Submitted to the Department of Electrical Engineering and Computer Science
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

at the

Massachusetts Institute of Technology

June 2017

© Massachusetts Institute of Technology 2017. All rights reserved

Author

Department of Electrical Engineering and Computer Science

Signature redacted

May 19, 2017

Certified by

James L. Kirtley

Professor of Electrical Engineering and Computer Science

Signature redacted

Thesis Supervisor

Accepted by

Leslie A. Kolodziejski

Professor of Electrical Engineering and Computer Science

Chair, Department Committee on Graduate Students

Signature redacted

L. U. J

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
ABSTRACT

Microgrid Risk Reduction for Design and Validation Testing Using Controller Hardware in the Loop

by

John Kendall Nowocin

Submitted to the Department of Electrical Engineering and Computer Science on May 19, 2017, in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Abstract

As electric power customers look for reductions in the cost of energy, increases in the level of service reliability, and reductions in greenhouse gas emissions a common solution is a microgrid. These microgrids are smaller power systems where distributed energy resources are used to power local electric load(s).

This work demonstrates an improved approach to planning microgrids via satellite imagery and has a case study in applied to India, the contribution of an anonymized real world test feeder to the power systems community, transition of geospatial information to a digital twin for an analysis of microgrid availability, and the process of developing a controller hardware in the loop platform to integrate physical equipment controllers from manufacturers and the development, testing, and validation of models by applying a general framework.

The controller hardware in the loop platform (CHIL) can achieve the testing capabilities for microgrid controllers as more functions are required. CHIL is one method to validate microgrid controller performance before equipment is installed. Microgrids promise to improve the reliability, resiliency, and efficiency of the nation’s aging but critical power distribution systems. Models of common power systems equipment were developed to achieve realistic interactions with the microgrid controller under test. The CHIL testbed that was built at MIT Lincoln Laboratory is described, and the equipment models developed are openly available. This testbed was able to test microgrid controllers under a variety of scenarios, including islanding, short-circuit analysis, and cyber attack. The effort resulted in the successful demonstration of HIL simulation technology at two Technical Symposiums organized by the Mass Clean Energy Center (CEC) for utility distribution system engineers, project developers, systems integrators, equipment vendors, academia, regulators, City of Boston officials, and Commonwealth officials. Actual microgrid controller hardware was integrated along with actual commercial generator and inverter controller hardware in the microgrid feeder that is becoming the IEEE reference standard.

Thesis Supervisor: James L Kirtley
Title: Professor
Acknowledgements

This document is dedicated to Kenneth Nowocin, my dad, for being there at critical points along the way, he will be missed. I would like to thank my family for being there to support me through this pathway to the PhD. My “ma” (Joanne Nowocin), mom (Ms. Jean Clayton), and MIT mom (Ms. Debb Hodges-Pabon) have pushed and comforted me when the going got tough. My partner Caroline helped me to stay balanced in being focused and guided while taking time to relax. The MIT graduate (Sydney Pacific) and undergraduate (East Campus) student housing has been instrumental in shaping the enjoyable social life on campus and providing me a balance. The Graduate Student Council and the Muddy Charles Board of Governors have allowed me to meet diverse graduate students across campus with the goal of improving the graduate student experience, and it was an honor to serve as President of the Graduate Body which represent over 6,800 MIT graduate students. The MIT Federal Credit Union Board and Supervisory Committee has provide encouragement and support to make positive changes and truely instills a people helping people mentality. The students and faculty in the High Voltage Research Laboratory, Laboratory of Electronic and Electromagnetic Systems, and Research Laboratory of Electronics have been my peers to share academic pursuits, have the passion for power systems, and explore new and novel directions in research. The Electrical Engineering and Computer Science Department along with Ms. Leslie Kolodziejski and Ms. Janet Fischer have been extremely supportive in my graduate school experience. MIT Lincoln Laboratory has been instrumental in guiding my research pathway. Mr. Erik Limpaecher and Mr. Scott Van Broekhoven have allowed me to take the lead on numerous projects and represent the group to internal and external sponsors.

My thesis committee members cannot be thanked enough. Professor Kirtley, Professor Leeb, and Mr. Bill Ross have provided life guidance, challenged me to push the bounds, helped and encouraged me when applying for funding, and most importantly allowed me the freedom and flexibility to explore and pursue my chosen pathway.

This achievement was a collaborative effort between MIT Lincoln Laboratory and industry microgrid controller manufacturers. This work was sponsored by the Department of Homeland Security (DHS), Science and Technology Directorate (S&T) and the Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability.
# Table of Contents

Abstract ................................................................................................................................. ii  
Acknowledgements .............................................................................................................. iii  
List of Figures ....................................................................................................................... vii  
Chapter 1: Introduction ...................................................................................................... 1  
  1.1 Power Systems ............................................................................................................... 1  
  1.2 Microgrids ..................................................................................................................... 6  
  1.3 Hardware in the Loop and Power System Testbeds .................................................... 8  
Chapter 2: Microgrid Planning ............................................................................................ 16  
  2.1 Gridform Overview ...................................................................................................... 16  
  2.2 Feature Extraction from Images .................................................................................. 17  
  2.3 Power System Planning Inputs ................................................................................... 17  
  2.4 Power System Planning Algorithm ............................................................................. 18  
  2.3.2 Power System Planning Results and Case Study .................................................... 22  
Chapter 3: Microgrid Analysis ............................................................................................ 31  
  3.1 MIT Lincoln Laboratory Energy Availability Study ................................................... 31  
  3.2 Background ................................................................................................................... 31  
  3.3 Scope ................................................................................................................................ 32  
  3.4 Analysis Tool ................................................................................................................. 33  
    3.4.1 Pseudocode of Generic Analysis ........................................................................... 33  
    3.4.2 Generic Framework for Microgrid Characteristic Information ............................... 34  
  3.5 Application to the Case Study ....................................................................................... 36  
    3.5.1 Case 0 and 1: Current Distribution (Spot Generation vs Central Generation) .... 38  
    3.5.2 Comparison of Microgrids .................................................................................... 39  
    3.5.3 Site Specific Recommendations of Infrastructure Change .................................. 43  
  3.6 New Microgrid Reference Model ................................................................................. 44  
Chapter 4: Microgrid Modeling and Control ....................................................................... 47  
  4.1 Framework ................................................................................................................... 47  
  4.2 Environmental Control Units to Smart Loads .............................................................. 48  
    4.2.1 Electromagnetics and Electromechanical .............................................................. 48  
    4.2.2 Primary Control ..................................................................................................... 49
List of Figures

Figure 1: United States power grid as of 2013 from geni.org. It shows the three sections of the Eastern Interconnection, the Western Interconnection, and the Texas Interconnection (ERCOT). Each operates at 60Hz, but given the larger area may be out of phase with each other. DC ties are used to share power from one section to the other. Source: https://www.technologyreview.com/s/401083/a-smarter-power-grid/ ........................................ 5

Figure 2: US power grid generation in 2017 by John Muyskens, Dan Keating, and Samuel Granados. Source: https://www.washingtonpost.com/graphics/national/power-plants/?utm_term=.740cfc48f910 .............................................................................................. 6

Figure 3: Microgrid Levels. Source: The Utility Grid of the Future – Challenges, Needs, and Trends. ............................................................................................................................................ 7

Figure 4: Overview of community level microgrids (shown in yellow) and there technical and policy challenges. ............................................................................................................................................ 7

Figure 5: Levels of power system testbeds from completely simulation and not physical controllers to the actual microgrid. Each system ranges in cost and the more realistic the system is the higher the cost. An analogy to planes is provided. .......................................................................................................................... 10

Figure 6: Test fidelity, coverage, and cost of different testbeds. ............................................................................................................................................ 12

Figure 7: Time step capability of a component. This can be used to determine the time step needed for the HIL platform. ............................................................................................................................................ 13

Figure 8: Bihar, India and the region of Munger. ............................................................................................................................................ 17

Figure 9: The villages found are highlighted with the colored polygons. ............................................................................................................................................ 17

Figure 10: Power planning algorithm flowchar. The step 2 spatial statistics analysis is a side process that can inform the selection of parameters to better train with the data collected. 18

Figure 11: Overview of the information to consider with defaults and recommendations listed. 19

Figure 12: Example of a component class with 2 cost curves to select from. ............................................................................................................................................ 20

Figure 13: Monte Carlo illustration for 1 and multiple generation nodes. ............................................................................................................................................ 21

Figure 14: Cost equations considered for the case example. ............................................................................................................................................ 22

Figure 15: Selection criteria for candidate villages. ............................................................................................................................................ 23

Figure 16: Process workflow of the case study. ............................................................................................................................................ 24

Figure 17: The original planned village 24 microgrid before anyone going to the site. ............................................................................................................................................ 25

Figure 18: Village houses and microgrid participants. ............................................................................................................................................ 26

Figure 19: Updated site load estimate given that 50 out of 65 participants. ............................................................................................................................................ 27

Figure 20: Total cost of village microgrid versus the number of generation nodes in the village. ............................................................................................................................................ 28

Figure 21: Wiring diagram of the village 24 microgrid. ............................................................................................................................................ 29

Figure 22: Village 24 site installation of microgrid. ............................................................................................................................................ 30

Figure 23: Flowchart of Microgrid Availability Analysis ............................................................................................................................................ 34

Figure 24: This is a representative figure of the monitoring network. ............................................................................................................................................ 36

Figure 25: Histogram of the Total Real Power used at the site over a year. ............................................................................................................................................ 37

Figure 26: Nodes of the case study power system. ............................................................................................................................................ 38
Figure 52: EPC Power inverter used for the battery and PV modeling. ................................. 69
Figure 53: The CHIL platform for the 2017 symposium was operated at a time step of 100us
  time step (10kHz). The EPC inverter gate drive signals were operated up to 5kHz (200us) and
  had double update rate capability which sampled every 100us (10kHz). ............................... 70
Figure 54: The electromagnetic and electromechanical model of the EPC inverter for the BESS.
....................................................................................................................................................... 71
Figure 55: Interface connection for the model to the physical EPC inverter controllers. ......... 72
Figure 56: Battery and PV Model of the EPC Inverter................................................................. 73
Figure 57: EPC Power inverter integrated in the CHIL platform ............................................. 73
Figure 58: HILLTOP Platform for the integration of physical controllers into the platform...... 75
Figure 59: HILLTOP Block Diagram for the physical controllers integrated into the platform. 76
Figure 60: Technology transfer effort and contributions from other collaborators .................. 77
Chapter 1: Introduction

1.1 Power Systems

The study of the fundamentals for power systems are based on the works of 19th century scientist in the field of mathematical physics. These scientist included Andre-Marie Ampere, Christian Orsted and Gian Domenico Romagnosi, Michael Faraday, James Clerk Maxwell, Oliver Heaviside, and Heinrich Hertz. Andre-Marie Ampere developed the mathematical form that characterizes magnetic forces between current carrying conductors and developed the theory of electromagnetism in 1820.[1] Christian Orsted and Gian Domenico Romagnosi were the firsts that observed the magnetic induction when he noticed a compass needle deflected away from north after a wire carrying current from a battery was switched on and off. Michael Faraday laid the foundation for the unification of electricity and magnetism which before 1873 was thought to be two separable forces. James Clerk Maxwell’s work extended the unification that the two forces interacted with each other and published A Treatise of Electricity and Magnetism. Oliver Heaviside and Heinrich Hertz partially reformulated this work and the accomplishments during this time period had far reaching consequences.[2]

These discoveries lead to the creation of power generation. The first devices that produced electrical energy required that the load was located nearby sometimes within the same room. In the 1880s, electricity began to compete with direct use of steam, hydraulics, and coal gas. Steam was used primarily for engines and pumps in industrial settings and several efficiency improvements occurred during this time. Hydraulics were mainly used in mining especially to successful extract gold-rich minerals during the California Gold Rush, but caused widespread environmental damage. Coal gas was the most prevalent because it could be produced at the customer’s site as a byproduct of solid coal. Gasification plants to this a step further by tapping into economies of scale. As the industrialized world grew, cities used piped coal gas networks for lighting though there were many disadvantages which included poor light, wasted heat that made rooms hotter, and noxious smoke, hydrogen, and carbon monoxide. This is why coal gas was quickly replaced by electric lighting.[3]

The history of early power systems was a battlefield for some, especially Thomas Edison and George Westinghouse or direct current (DC) versus alternating current (AC). In 1882, Thomas Edison established the first investor-owned electric utility (Edison Electric Light
Company) and based it on his patented DC power. Four years later (1886), George Westinghouse started with DC, but not being locked into the technology and seeing the potential competitive edge of AC from the UK technical journal *Engineering* quickly switch to AC the following year. This war took on three fronts: open and cut-throat competition of large electric companies with the different developing systems, media and propaganda campaigns, and creation of the public’s fear of death and safety with high voltage AC. The two main forms of lighting were arc lights which required high voltages (greater than 1,000V), lit up large areas, and were suitable for outdoors; and incandescent lights which worked on low voltage (less than 200V), indoor use for businesses and residential use. Edison in particular used 100V, and then later a dual ±100V. Many lighting companies were formed over a 5-10 year period because of the market desire for cleaner lighting though there were large capital and development costs for this new technology. Electric utility companies took advantage of economies of scale.[4] The power flow model can be visualized as a car driving down a one way street. The car represents the electrons flowing and the direction of the car is one way going from a centralized power generation plant, to transmission, to distribution, and then to loads. With long distance AC power transmission it became possible to interconnect stations to balance load and improve site power factors. By the 1890s over 15 companies had merged to take effects of economy of scale into the three: Edison (later Edison General Electric), Thomson-Houston, and Westinghouse. A propaganda war started in 1888 when AC was gaining ground on DC and Westinghouse was the main target because of acquiring most of the AC patents in the US. The propaganda included public demonstrations of electrocutions of animals and Howard P. Brown writing several public articles and consulting for the City of New York to make the electric chair AC.[5] The fundamentals of AC having an increase in efficiency over DC for long transmission distances and ability to step up and down the voltage ultimately provided the competitive edge to win out. The war concluded in 1890 with Thomas Edison leaving the electric power business after becoming marginalized and losing controlling stake in the merger that formed Edison General Electric, and the Edison Machine Works started development on AC based equipment.[6]

In industrialized areas outside the United States, power systems were being built and expanded. The most prominent in Europe were the United Kingdom and France. In 1901, the Neptune Bank Power Station (near the Thyne River of Newcastle, United Kingdom) was built by
Charles Merz, of the Merz & McLellan consulting partnership, and in 1912 became the largest integrated power system in Europe.[7] The UK’s Parliamentary Committee appointed Merz as chair and the committees work led to the Williamson Report of 1918. This caused the creation of the Electricity Supply Bill of 1919 which focused on an integrated electricity system to increase stability and expansion. A “National Grid” was setup with the Electricity Supply Act of 1926 and standards were established and regulated by the Central Electricity Board. The standard established the first synchronized AC grid, transmission operation at 132kVac, and a 50 Hertz frequency. The electrification in France began around 1903, and grew almost exponentially with 700 communes/districts (by 1919) to 36,528 (by 1938). The explosive expansion was due to small territorial areas being interconnected at higher voltages and longer distances: 12 kV in Paris (1907), 150kV in Pyrénées (1923), and 220kV for all of France (1938). In 1946, France nationalized the industry by uniting the private utilities into a public company with the largest owner being the French government called Électricité de France, and became the world’s most dense power system at the time. They standardized on transmission operation at 225kVac and 50Hz frequency, and in 1970 increased it to 400kV which became the European standard.[4]

In the United States a different approach of distributed utilities working together was used. In the 1920s, utilities formed joint-operations to share peak load coverage and backup power which stabilized and expanded the power system. In 1934, electric utilities were recognized as public goods of importance. The passing of the Public Utility Holding Company Act (PUHCA) gave them the ability to outline restrictions and gave them regulatory oversight of their operations. The power system industry expanded the network and grew into larger vertically integrated utilities. A vertically integrated utility refers to generation, transmission, and distribution being owned by the same company and can allow for increased efficiency from economies of scale. This regulated monopoly was brought into question during the late 1980s to early 1990s, and deregulation came. Several reports and studies were done on the deregulation benefits in Great Britain.[8] The Energy Policy Act of 1992 was passed which amended PUHCA and the Public Utility Regulatory Policies Act (PURPA) of 1978. It required the owners of the transmission line to open access to their lines. The goal was to create competition in the power generation space by allowing more generation companies to access loads through the transmission system and created restructuring of the how the electric industry operated. The
previous status quo of operating as vertically integrated utilities which was a regulated monopoly was changed. The federal law opened the doors to competition. The goal was to favor the concept of a more competitive marketplace being more efficient and lower cost to consumers. Generation, transmission, and distribution could be split among companies and fair accessibility to high voltage transmission was achieved. The concept of power flowing one direction (from generation to transmission to distribution to the load) was still considered the main assumption and was not brought into question. This deregulation took hold in many parts of the US, and Independent System Operators (ISOs) were formed to provide regulatory and operational oversight. This has not been the case in all parts of the US; for instance, the southeast does not have an ISO and there are many vertically integrated utilities (i.e. Santee Cooper) still in existence. The Energy Policy Act of 2005 allowed incentives and loan guarantees for alternative energy production and advance innovative technologies that avoided greenhouse emissions.

The current state of the US power grid from the transmission perspective can be seen in Figure 1. It shows the three sections: Eastern Interconnection, the Western Interconnection, and the Texas Interconnection (ERCOT). Each operates at 60Hz, but given the larger area may be out of phase in time with each other. DC ties are used to share power from one section to the other. The system has been built up over several decades and massive investment from the federal government and cooperatives. As of 2017, the rule of thumb rough costs for a transmission line above 69kV is around $1.25M a mile for overhead and double that for underground. As more power is consumed, one costly solution is to add additional power lines to accommodate this increased demand. It should be noted that more rigorous analysis would be done on the project before costs are passed to rate payers.
Figure 1: United States power grid as of 2013 from geni.org. It shows the three sections of the Eastern Interconnection, the Western Interconnection, and the Texas Interconnection (ERCOT). Each operates at 60Hz, but given the larger area may be out of phase with each other. DC ties are used to share power from one section to the other. Source: https://www.technologyreview.com/s/401083/a-smarter-power-grid/

The US power plant generation types, location, and power size can be seen in Figure 2. It compromises of natural gas, coal, nuclear, hydroelectric, wind, solar, oil, and other (ie. biomass, new technology etc.). These existing and newer technologies can be used at a variety of power scales. The trend of generation has been coal drastically decreasing and being replaced by natural gas due to lower gas prices. Renewables such as wind and solar have been increasing almost exponentially. The main locations of wind are in the Midwest and solar in the southern portions of the US, respectively.
1.2 Microgrids

Microgrids challenge the long standing model that power flows from central generation to the load. A microgrid has generation located at the site of the load. The existing or new local generation can be utilized to power a single or multiple customers, and bidirectional power flow can occur. This changes the fundamental assumption of power flowing one way on traditional power system (which is from central generation to the load). The components that comprise microgrids – distributed energy resources (DERs), protection equipment, and distribution equipment – are complex systems in and of themselves. When combined to form a larger system, with nearly infinite possible combinations, these microgrids can exhibit unpredictable behavior.

The focus of this thesis is on US power systems is from 1 to 50 MW. This range falls into the classification of partial feeder to full substation microgrids and has multiple customers. The power size is sufficient enough to operate in power system markets where they exist. A high level segmentation of the grid for community level microgrids are shown in Figures 3 and 4.
Community Microgrids

- Cost-effective, nationally deployable multi-customer microgrids
- Many recent studies...no actual execution
  - Sandia “Advanced Microgrids” study (Mar 2014)
  - “Microgrids ...for the Commonwealth of Massachusetts” (Feb 2014)
  - “Minnesota Microgrids” (Sep 2013)

Challenges
- Technical
  - Regional resilience analysis: site selection
  - Microgrid site design
  - Economical systems integration
  - Safe grid interconnection
  - Stable islanded operation
- Policy
  - Coordination with public utilities commission
  - Framework for utility involvement
  - Financial pro forma for real estate developers

Figure 3: Microgrid Levels. Source: The Utility Grid of the Future – Challenges, Needs, and Trends.

Figure 4: Overview of community level microgrids (shown in yellow) and there technical and policy challenges.
1.3 Hardware in the Loop and Power System Testbeds

A controller hardware-in-the-loop (C-HIL) testbed allows models and simulation to interact with physical controllers via an interface of analog and digital signals. The benefit of such a testbed is the ability to simulate varied and complex power system scenarios in software, yet be able to determine how actual hardware devices would respond as if they were actually deployed in the field. This leads to a decrease in capital investment for laboratories, and an increase in the speed of development of testbed scenarios. The expensive constraints of having to build a full-power system to test are removed.

As microgrids continue to be developed, increases in the capability and functionality will result. A master controller(s) makes the high level decisions ensure the microgrid is reliable and efficient. However, to date, there has not been a standard model for microgrid controller developers, and no testing standards have been officially adopted. In collaboration with the Energy Systems group at MIT Lincoln Laboratory, the different capabilities of hardware in the loop (HIL) vendors was surveyed and a C-HIL testbed for microgrid controllers to be tested using an OPAL-RT real-time digital simulator was setup.

As a result, extensive and project-specific integration and interoperability testing are essential to ensure safe and reliable operation under the wide range of possible operating conditions. Microgrid controllers act as the nerve center of microgrid systems, tying together and coordinating the DER and other components. Microgrid controllers and the secondary and primary controllers they interact with are a main challenge of microgrid deployment. Numerous issues, however, have been identified by industry as an impediment to efficient microgrid deployment.

- High non-recurring engineering (NRE) cost: Each project has a high NRE due to the project specific integration and interoperability testing required.
- “Vaporware”: As new companies enter the market for microgrid controls, and established companies modify their existing products to address this new business opportunity, some have been accused of advertising functional capabilities that are not yet ready. When the time comes for deployment, it becomes apparent due to delays in deployment that these functions are under development and the project is the first demonstration of the capabilities.
- Risk of damage to expensive equipment: As cyber-physical industrial control systems, microgrid controllers and downstream controllers can malfunction and cause real physical damage to multi-megawatt pieces of equipment, with the associated cost, schedule, and safety concerns.
- Uncharacterized controls behavior: Because their controls behavior relies on proprietary software, the interconnection behavior of a microgrid – or even standalone DERs – is largely unknowable to utility power distribution engineers using existing industry engineering tools. The steady-state and transient analysis tools used by distribution system engineers cannot assess the dynamic control behavior of these new assets and systems.
- No standards verification: IEEE 1547 only covers subset of operations which include grid tied and anti-islanding operation. Industry-wide standards for microgrid controllers are nascent: IEEE is developing the P2030.7 Standard for the Specification of Microgrid Controllers, as well as P2030.8 Standard for the Testing of Microgrid Controllers; Duke Energy and its partners are developing the OpenFMB framework; and distribution utilities are just beginning to consider their own specific regulations. Currently, no methods exist for cost-effectively testing microgrid designs against these standards or the requirements defined by project developers or end users.

A technology platform that facilitates the design, evaluation, commissioning testing, and standards compliance validation testing of microgrids could accelerate deployment of microgrids. The major advantages to this approach are risk reduction when integrating new technology, lower cost to test operation, and larger range of tests that can be performed to validate correct controller operation. The industry needs software development and integration work completed well in advance of construction of the microgrid. Projects would see a higher approval rate if the utility engineers and project developers perceived lower technical, safety, and financial risk. Due to the integration and testing challenges introduced by microgrid systems, this platform should focus on microgrid controllers and the assets they integrate. Microgrid testbeds – and advanced distribution testing – can be separated into five categories, shown in Figure 5.
Three main questions can be asked to determine which level of power system testbed is desired.

- **Testbed Cost**: How much does the testbed cost to build, develop, and operate? When unused, how much does it cost to maintain the testbed facilities and personnel experience?
- **Test Fidelity**: How accurate is the test? How true is the system's behavior to the behavior exhibited by the final deployed microgrid?
- **Test Coverage**: How much of the operational range can be tested? Can potentially dangerous or damaging "edge conditions" be tested without risking the test equipment?

The ends of the power system testbed spectrum can be defined. At the low-cost, low-fidelity, high-coverage end of the spectrum are software-only simulations, which use tools to include but not limited to MATLAB SimPowerSystems, CYME, and Powerworld. While this approach enables the evaluation of the full range of test conditions at the lowest cost, it usually...
cannot incorporate actual control behavior of the DER and protection equipment. The proprietary software implemented by vendors on the DER is almost never available for inclusion in the model. At the opposite end of the spectrum are the actual, fully built microgrids. These provide the highest fidelity, but at a high cost and limited test coverage due to the risk of damage to expensive components.

As an example of a full system, one utility deployed a small battery-based microgrid to support a critical facility. Due to a lack of other testbeds, the utility performed the vast majority of its testing on the microgrid’s final deployed equipment. After a year of testing, upon connection of the battery to the critical load, the utility discovered that it had destroyed a 750 kVA transformer during high ramp-rate testing of the energy storage system’s controls. The controls of the system overloaded the transformer which caused it to heat up, the coolant to boil, and then exploded.

Power testbeds, where the DER components are scaled down in size, provide some cost relief at the expense of test fidelity. The National Renewable Energy Laboratory’s (NREL) Energy Systems Integration Facility (ESIF) and Oak Ridge National Laboratory’s (ORNL) Distributed Energy Control and Communication (DECC) laboratory are examples of this type of testbed. Power HIL testbeds typically place one piece of power equipment under test and simulate the behavior of the remainder of the power system. The Florida State University’s (FSU) Center for Advanced Power Systems (CAPS) provides the Navy such a testbed. A 5 MW ABB power converter recreates the voltage waveforms of a simulated shipboard power system to test new shipboard power equipment. The ESIF has similar facilities, focused on domestic DER applications. Controller HIL testbeds place all the expensive, potentially dangerous, high-voltage, high-power equipment into a real-time simulation. Unlike a pure simulation, the actual device controllers are placed on the benchtop and interfaced to this simulation. The controllers, running the actual, proprietary control code that will be used to control the real microgrid assets, are configured as if they were operating real DERs, protection devices, and distribution equipment. This provides highly representative system behavior and allows the testing of a full range of edge conditions without risking damage to any equipment. The primary challenge with this approach: development of validated models of the power equipment.
Due to the attractive tradeoff between low testbed cost, good test fidelity, and excellent test coverage, MIT Lincoln Laboratory (MIT LL) focused on developing hardware-in-the-loop for microgrid controllers as a way to accelerate adoption of microgrids by facilitating realistic demonstrations, enabling risk reduction testing, and enabling pre-commissioning systems integration and testing.

(Figure 6: Test fidelity, coverage, and cost of different testbeds.)

The testing that can be done with hardware in the loop platforms is extensive. The test coverage can include but is not limited to reactions of the controller to short circuit test, open circuit test, disconnection of measurements like CT’s and PT’s, loss of analog and digital signals, commanded oscillations to see any resonances form, loss or overloading of the communications, and protection function capabilities. C-HIL has the ability to cover a large array of testing without the risk of damaging equipment. Figure 6 shows the capabilities of HIL platforms.

12
High-Coverage Real-time Simulation

- Microgrid controller HIL simulates in real-time at sub-cycle timescales

Useful for:
- Steady-state
- Dynamic analysis
- Transient analyses

Figure 7: Time step capability of a components. This can be used to determine the time step needed for the HIL platform.

The vision for this work is to create a standardized demonstration and evaluation platform for any available commercial microgrid or device controller in the market using any distribution system topology. The outcome of this work will reduce microgrid development cost, validate marketing claims, and reduce risk of equipment damage, as well as reduce deployment time. The stepwise approach for building this platform is as follows:

1. Microgrid feeder: Model the target microgrid distribution feeder and segment it into the processing cores of a real-time digital simulator. Multiple vendors sell real-time simulators, including but not limited to OPAL-RT, Typhoon HIL, RTDS, and National Instruments. For this effort, MIT LL selected an OPAL-RT 5607, partly because it could accept models from MATLAB SimPowerSystems. The feeder is a physical real world site and the location and other identifying information has been removed to make it an anonymized feeder. Access to the detailed specifications of the transformers, conductors, protection devices, and loads was available.
2. Load and irradiance profiles: Assigned a priority of Critical (served 100% of the time even with a grid outage), Priority (could be de-energized during a grid outage, but needed to be reconnected as soon as possible), or Interruptible (could stay de-energized during a grid outage) to each load. Collect real load measurements on the test feeder at one second intervals. A one second is the typical fastest continuous data logging setting of Commercial Off The Shelf (COTS) power monitors. Collect a solar irradiance profile to simulate representative variation in solar energy production.

3. Distributed Energy Resources (DER) devices: Develop models of the physical DER devices, including gensets, a battery-based energy storage system with a bidirectional power converter, a solar photovoltaic (PV) system with inverter, and eighteen breakers. (Future work will require either validation of these models or replacement with vendor-provided models.)

4. Physical device controllers: Commercial diesel generator controllers with the simulated microgrid power devices were integrated into the platform. A signal conditioning interface was designed and built, the simulation of the physical genset and its subcomponents was created, and calibration / configure of these controllers as if they were operating actual 1 MVA and 4 MVA, 13.8 kV generators was done.

5. Software device controllers: Ideally, all of the controllable devices within the test would be operated by actual commercially available controllers. For those microgrid devices that are not operated by a commercial controller, develop custom control software. (For this project, this was done for the energy storage, solar PV, and breakers.) Implement several relay protection functions to actuate the breakers. Implement various control schemes – real/reactive power control, frequency and voltage control, maximum power point tracking within the PV inverter – on the DER controllers to enable the microgrid controllers flexibility in how they operated the system.

6. Manual testing: Once the elements listed above are successfully integrated, engineers can operate the microgrid by manually issuing dispatch commands and changing operating setpoints within the system. Using the developed software interface, a test of the Modbus TCP/IP communications protocol can be performed on each device.
7. Additional test stimuli: Simulate grid outages, inrush currents from motor starts, and faults in various locations of the system in real time to increase the realism of the simulation. (For this initial demonstration, none of these additional stimuli were introduced. Intentional microgrid islanding – not unintentional islanding – was implemented by the microgrid controllers.)

8. Microgrid controllers: Lastly, integrate commercial microgrid controllers in collaboration with these companies’ engineers. (Schneider and Eaton controllers were integrated for this demonstration.) Protocol converters may be needed to translate the communications from the microgrid controller to Modbus TCP, and to map the microgrid controller’s register list to the communication registers used by the software and hardware device controllers.

9. Test and collect data: Execute test sequences under a variety of load, irradiance, fault, and grid stimuli. Collect communications data, estimated fuel consumption, power generation, data on voltage and frequency quality, and load service information.

10. Post-process data for performance metrics: Use the data to quantify performance of the microgrid controllers, compare performance between vendors, and identify potential areas for additional testing and development.

The time step needed for the HIL platform depends on what is being tested. Real-time simulators are commonly used to design and evaluate power system controls and protection equipment. Figure 7 shows the typical simulation timescales required for a variety of applications and studies in the power system. The right-side of the figure describes the slow dynamics, such as load profiles, irradiance data, and mechanical systems. Simulations of this nature generally require a solution-step or time-step at 10 milliseconds or less to maintain numerical stability. The conventional steady-state power-flow studies are also considered slow simulations (60 Hz) since they are not able to reflect the transient effects of switching events and faults. Consequently, power-flow simulations cannot be used to assess power system transients, the behavior of device controllers, or generator protection. That is because these events/components operate in the kHz range and require faster simulation solutions. The time step selected was 80 or 100 microseconds.
Chapter 2: Microgrid Planning

2.1 Gridform Overview

The first stage of a microgrid is a plan, which provides sufficient information about the system such as a one line diagram, proper sizing of equipment to meet the desired goal, components to be integrated, and cost of the project. A new deployment may not have any of this information and a trained engineer(s) are needed. The fundamental question is how to rapidly develop a microgrid plan, and this work will be further applied to a case example in India.

A critical factor in planning power systems is the geospatial information. Power system planners are currently working toward digitizing the US grid. A digital twin is a model of the physical system and can be used to perform analyses and studies. These studies include but are not limited to impact of planned expansions to the grid, added generation to a feeder by an interconnect agreement, design of protection schemes, load flow studies, and transient analysis caused by faults. The current process of doing this in developed countries is tedious and time consuming, and is almost nonexistent in developing countries. As satellite imagery becomes more readily available and the quality and resolution increase, then new methods of planning can emerge because of the new information available. A focus on creating an algorithmic approach for microgrid planning using geospatial information in developing countries rural areas will be described, and the details of feature extraction from images can be found in reference 11.

Satellite imagery can be considered a form of big data that can be harnessed for many social good applications, especially those focusing on rural areas. A common problem is selecting sites and planning rural development activities as informed by remote sensing and satellite image analysis. The current power system planning approach in India for rural areas was done by site surveys and hand drawn maps which is difficult to scale by any means other than algorithms for estimation and inference from remotely sensed images. In India, since 300 million people do not have access to energy the process has to scale. The application of the technology was applied to a case of siting and planning of solar-powered microgrids in remote villages in Bihar, India.
2.2 Feature Extraction from Images

A region of 50 square km was chosen by our partner organization SELCO in Bihar, India. Figure 8 shows the region and images to extract. The satellite imagery was purchased from Apollo Mapping.

Figure 8: Bihar, India and the region of Munger.

There were approximately 100 sites and 10,000 houses detected and polygonised within the two regions. Three candidate sites were selected and planned.

Figure 9: The villages found are highlighted with the colored polygons.

2.3 Power System Planning Inputs

The data and excel spreadsheets can be seen in the appendix.
2.4 Power System Planning Algorithm

The algorithm flowchart is shown in Figure 10. The geographic information system file also known as a shapefile is imported into Matlab. The polygons of each house are extracted and statistics on size, shape, and location are used to determine the sites specific parameters and weighting for the load estimator. A monte carlo simulation where the user can define the number of iterations to run per generation node (default is 10,000 iterations) is performed to determine the total cost of the system. The lowest system costs are identified and plotted. A shapefile of the one line diagram and other calculations are outputs to the user.

Step 2 - Spatial statistics analysis

Figure 10: Power planning algorithm flowchart. The step 2 spatial statistics analysis is a side process that can inform the selection of parameters to better train with the data collected.

A generic expandable excel spreadsheet was developed to create a catalogue of potential components that could be selected for deployment in the microgrid. This creates a parametric space and the algorithm can select these discrete points or perform a parametric sweep over a components cost curve(s). The code selects components based on the estimated site load, voltage drop, user defined backup power and hours of use without generation, and user defined safety
From the practitioner's perspective, discrete points or components are selected which results in bill of materials of real components that can be purchased and increases the accuracy of the cost estimate. Figures 11 and 12 show an example of the Excel spreadsheet. As additional classes of items are to be considered an additional sheet is added and numbered and the Matlab code recognizes the additional information and can be rerun on the new information.

Figure 11: Overview of the information to consider with defaults and recommendations listed.
Figure 12: Example of a component class with 2 cost curves to select from.

This Excel information is imported automatically into the Matlab when the code is run, and the user only has to start the code. The code was developed to take advantages of parallel processing and matrix manipulations which reduce the computation time from 3 days to 1 hour on a the same laptop which had 2 cores. The user can see selection of the components being chosen in the parametric space created for components and sets of components. The output is an Excel workbook of the components, cost, and location of components which is accompanied by a georeferenced layout of the system to wire and cost charts.

A Monte Carlo simulation was performed to determine the optimal placement of generation and power sharing nodes. A generation node is defined as power producer and is a polygon location that was digitized into GIS information which is imported into the program. A load node is a power consumer and in this case is a physical house. The polygon information is used to determine generation and or load size that can be put at that location. To determine the optimal location of generation node(s), a polygon is selected at random and made a generation node. This generation node can is then connected to the rest of the polygons now classified as loads. The connection method can be a nearest neighbor connection, straight line direct connection of generation to load nodes (called hub and spoke), main bus/branch and trunk to load nodes, or a minimum spanning tree. The hub and spoke model was preferred by
practitioners on the ground because of its ease of setup and ability to connect additional users that buy into the system after it is installed and operational. This process of randomly selecting the node location and increasing the generation nodes would typically result in convergence after 200-300 iterations. The user can choose the number of iterations to perform and 1000 iterations is the default and is used for code performance comparison. Figure 13 illustrates the Monte Carlo process for 1 and multiple nodes.

**Figure 13: Monte Carlo illustration for 1 and multiple generation nodes.**

The code for the program was designed in a modular way. As a new aspect to consider is needed to be added or a better estimator is developed the old module can be “unplugged” from the code and the new module can be “plugged” in its place. These code modules compute the various cost equations that go into determining the user defined optimization function. Figure 14 shows the various cost equations that were considered for the case.
- **Building and Line Loss**
  \[
  \text{Building and Line Loss} = \left( \frac{\text{Each House's Load (Estimate)}}{1000} \right) + \left( \frac{\text{Node to House Distance} \times (\text{Wire Cost} + \text{Mounting Hardware} + 5\text{m of internal house wiring})}{\text{Distribution Voltage}} \right)
  \]
- **Solar Panel**
  - Cost of Power from Solar Panels * (Building and Line Loss)
- **Battery**
  - Cost of Power from Batteries * (Building and Line Loss)
- **Wiring**
  - Node to House Distance * (Wire Cost + Mounting Hardware + 5m of internal house wiring)
- **Labor**
  - Node to House Distance * (Labor Rate * Man Hours * Technician Number) + 2 * Flat Rate to Connect Power
- **House Converter**
  - House Converter Box
- **Site House Total**
  - \( \Sigma (\text{Building and Line Loss} + \text{Panel} + \text{Battery} + \text{Wiring} + \text{Labor} + \text{House Converter}) \)
- **Power Node Battery Regulator and Converter/Inverter**
  - \( \Sigma (\text{Node Battery Regulator} + \text{Node Converter Cost}) \)
- **Power Node Wiring**
  - \( \Sigma \text{Node to Node Distance} \times (\text{Wire Cost} + \text{Mounting Hardware}) \)
- **Power Node Labor**
  - \( \Sigma \text{Node to Node Distance} \times (\text{Labor Rate} \times \text{Man Hours} \times \text{Technician Number}) + \text{Labor Cost of Node} \times \text{Node Number} \)

**Figure 14**: Cost equations considered for the case example.

The output of the code is an Excel document that includes a bill of materials, the cost of each house to the total system cost, the power of each load/house, the power of the generation node, the cost of each component of the system, and other user-selected information. A GIS map of the village that is color-coded to high, medium, and low costs of connecting each house is determined based on the standard deviation from the average. This allows the project developer to visualize the expensive aspects of the project, and helps the user to determine if certain selection criteria should be reconsidered or relaxed. This information can be incorporated back into the excel input and the code rerun on a laptop computer in the field to provide real-time feedback with the customer.

### 2.3.2 Power System Planning Results and Case Study

The selection criteria, images of the village before and after planning, along with a cost comparison of the traditionally and Gridform planned solutions will be shown. The selection criteria from the 100 candidate sites in the region is shown in Figure 15. The Indian Rupee (INR) was approximately 68 INR to $1 USD. All 100 sites were designed using the Gridform tool and
the candidate sites were rank ordered, grouped into tiers based on the size and location, and had an estimated cost before anyone had gone to survey the village. This information can be seen in Table 1. The Gridform selection process resulted in a significant reduction in man-hours to selection, survey, design, and plan the site, and travel costs to survey and redesign the microgrid from on the ground observations. Table 1 was not shown to Selco’s Microgrid Development team in order to keep the traditionally planned unbiased. For this case study village 20 was selected as the traditional planned site and village 24 as the Gridform planned site.

- **Cost (removal criteria)**
  - Cost/Building: \(< \text{₹}12,600/\text{house}\)
  - Total Project Cost: \(< \text{₹}1,000,000\)

- **Size and Location (comparison criteria)**
  - Size: Number Houses
  - Topology: Number of Nodes
  - Location: Adjacent villages with similar economies

- **Site Visit Considerations**
  - Availability of Electricity
  - Demographics
  - Economy

*Figure 15: Selection criteria for candidate villages.*
Table 1: Subset of rank ordered villages that met the selection criteria to be considered for microgrid deployment.

<table>
<thead>
<tr>
<th>Village ID</th>
<th>Houses</th>
<th>Cost/Building (₹)</th>
<th>Total Project Cost (₹)</th>
<th># Nodes</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Village 20</td>
<td>46</td>
<td>₹ 9,956</td>
<td>₹ 457,980</td>
<td>6</td>
<td>Strong</td>
</tr>
<tr>
<td>Village 14</td>
<td>42</td>
<td>₹ 11,891</td>
<td>₹ 499,440</td>
<td>7</td>
<td>Strong</td>
</tr>
<tr>
<td>Village 24</td>
<td>54</td>
<td>₹ 11,023</td>
<td>₹ 595,288</td>
<td>9</td>
<td>Strong</td>
</tr>
<tr>
<td>Village 52</td>
<td>14</td>
<td>₹ 10,412</td>
<td>₹ 145,774</td>
<td>1</td>
<td>Medium</td>
</tr>
<tr>
<td>Village 49</td>
<td>22</td>
<td>₹ 9,865</td>
<td>₹ 217,022</td>
<td>1</td>
<td>Medium</td>
</tr>
<tr>
<td>Village 51</td>
<td>38</td>
<td>₹ 11,099</td>
<td>₹ 421,763</td>
<td>2</td>
<td>Medium</td>
</tr>
<tr>
<td>Village 13</td>
<td>22</td>
<td>₹ 9,300</td>
<td>₹ 204,609</td>
<td>1</td>
<td>Weak</td>
</tr>
<tr>
<td>Village 10</td>
<td>34</td>
<td>₹ 9,992</td>
<td>₹ 319,343</td>
<td>5</td>
<td>Weak</td>
</tr>
<tr>
<td>Village 45</td>
<td>44</td>
<td>₹ 9,421</td>
<td>₹ 414,504</td>
<td>5</td>
<td>Weak</td>
</tr>
<tr>
<td>Village 17</td>
<td>14</td>
<td>₹ 9,954</td>
<td>₹ 139,351</td>
<td>10</td>
<td>Weak</td>
</tr>
<tr>
<td>Village 15</td>
<td>46</td>
<td>₹ 11,771</td>
<td>₹ 541,473</td>
<td>14</td>
<td>Weak</td>
</tr>
<tr>
<td>Village 53</td>
<td>50</td>
<td>₹ 11,576</td>
<td>₹ 578,816</td>
<td>13</td>
<td>Weak</td>
</tr>
<tr>
<td>Village 12</td>
<td>66</td>
<td>₹ 10,841</td>
<td>₹ 715,507</td>
<td>4</td>
<td>Weak</td>
</tr>
<tr>
<td>Village 2</td>
<td>64</td>
<td>₹ 11,316</td>
<td>₹ 724,192</td>
<td>3</td>
<td>Weak</td>
</tr>
<tr>
<td>Village 18</td>
<td>78</td>
<td>₹ 11,060</td>
<td>₹ 862,698</td>
<td>15</td>
<td>Weak</td>
</tr>
<tr>
<td>Village 41</td>
<td>78</td>
<td>₹ 11,398</td>
<td>₹ 889,077</td>
<td>14</td>
<td>Weak</td>
</tr>
<tr>
<td>Village 33</td>
<td>84</td>
<td>₹ 10,611</td>
<td>₹ 891,327</td>
<td>6</td>
<td>Weak</td>
</tr>
<tr>
<td>Village 32</td>
<td>78</td>
<td>₹ 11,942</td>
<td>₹ 931,485</td>
<td>17</td>
<td>Weak</td>
</tr>
<tr>
<td>Village 27</td>
<td>82</td>
<td>₹ 11,982</td>
<td>₹ 982,551</td>
<td>17</td>
<td>Weak</td>
</tr>
</tbody>
</table>

The process of case study is shown in Figure 16, and the resulting times are shown in Table 2.

![Figure 16: Process workflow of the case study.](image)

Table 2: Number of days to complete phases of the project.

<table>
<thead>
<tr>
<th></th>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
<th>Phase 4</th>
<th>Phase 5</th>
<th>Phase 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional</td>
<td>N/A</td>
<td>N/A</td>
<td>14 days</td>
<td>21 days</td>
<td>21 days</td>
<td>6 days</td>
</tr>
<tr>
<td>Gridform</td>
<td>7 days</td>
<td>1 day</td>
<td>3 days</td>
<td>1 day</td>
<td>21 days</td>
<td>3 days</td>
</tr>
</tbody>
</table>
In phases 1 and 2 it was assumed that all the houses identified would be provided power from the microgrid (see Figure 16), but the information from phase 3 changed this assumption completely. After visiting the sites it was clear that the residents of the village were skeptical of being provided power because of previous false promises from other people/entities. This resulted in a subset of the houses in the village deciding yes or maybe to participate in the microgrid. Figure 17 shows that 50 out of the 60 houses were willing to participate in the microgrid. The Gridform program was designed to be flexible and rapidly take new information into account to redesign and optimal solution for the user.

Figure 17: The original planned village 24 microgrid before anyone going to the site.
The black polygons are the 65 houses originally identified. The site survey identified 10 "maybes" shown in yellow, and 40 "yeses" shown in green. The village to be planned is the yeses plus maybes (50 houses).

Figure 18: Village houses and microgrid participants.

This information was used to quickly rerun the code and resulted in an updated load estimate of each house which could be verified with the participants, cost curve of the total village cost, and selection of the optimal design for lowest cost or the user's choice of a design. The load estimator takes into account area of the house, location to the village center, and nearest neighbor load estimate to determine the best guess for load power usage, and the result is shown in Figure 19.
The updated cost estimate curve is shown in Figure 20. On the x-axis is the number of generation nodes that the site would have. A one generation node at the site means that there is a central generation point for the entire village. In some villages a central generation point is the cheapest and those areas tend to be more densely packed. On the other extreme if 18 generation nodes were placed this would mean more of a solar home lighting kit approach. In some villages a solar home lighting system is the cheapest and those areas tend to be more spread out. For this village 4 generation nodes placed throughout the resulted in the lowest estimated total village cost. The breakdown contribution to various factors (i.e. load, house converter, solar panels, battery, power electronics converter, labor, and etc. can be seen). The blue straight line curve is the equipment cost of the lowest power/capital cost solar home lighting kit multiplied by the number of houses in the village to get the total capital cost of the village. The black line is the equipment cost of the planned microgrid, and it should be noted that the power provided to the village by the microgrid (1,980 W) is approximately 3 times greater than the power provided by the solar home lighting kits (650 W). The green line is the solar home lighting kit equipment cost plus the labor cost to install. Therefore, the blue and black lines represent equipment, and the green line and bar peaks represent the equipment plus labor estimates.
Figure 20: Total cost of village microgrid versus the number of generation nodes in the village.

The practitioners on the ground were surprised by the finding that the total cost of the site would be less if a central generation source was not deployed. They were skeptical of this, but proceeded with the Gridform planned solution. The optimal lowest cost design was 4 generation nodes. However, the practitioners mentioned that because they had not done a distributed generation microgrid before, that a 3 generation node microgrid would be easier to install and much lower on labor cost. Figure 21 shows the Gridform wiring design chosen by the user and was used on the ground during installation. It should be noted that in a later site visit the 1 node removed from the 4 to 3 node design was beneficial because the owner of the house was not willing to have solar installed on their roof and the house structure was not sufficient to support the solar panels.
A subset of the site pictures during installation can be seen in Figure 22 and in the Appendix. The result of the two installations was approximately 400 people now have access to energy that did not have it previously.

Figure 21: Wiring diagram of the village 24 microgrid.
Figure 22: Village 24 site installation of microgrid.
Chapter 3: Microgrid Analysis

3.1 MIT Lincoln Laboratory Energy Availability Study

A wide variety of technologies are being considered for integration into microgrids. These technologies could replace legacy spot backup diesel generators which are co-located next to emergency or critical loads, cogeneration plants, distribution switchgear for ring and zonal distribution topologies, and a wide variety of energy storage systems. Questions arise about whether microgrid systems would actually be more available and reliable than legacy backup generation. The increased complexity and larger footprint than back-up spot generation may likely reduce the availability, especially under adverse environmental conditions, but the full system may still in sum be more available than any individual subsystem. Subsystems within a microgrid tend to operate regularly during nominal conditions – as opposed to backup generators, which may sit idle for extended periods – increasing a microgrid’s accessibility. This work in collaboration with MIT Lincoln Laboratory (MIT-LL) and MIT aimed to answer these questions by quantifying the probabilistic reliability of various microgrid configurations, comparing them to the reliability of existing backup solutions, and providing a visual tool to identify critical points of the system. The tool is flexible enough to work on a generic power system and is scalable in size. A list of recommendations and future progress such as (cost benefit analysis, etc.) was created based on the anonymized power system and provided to customers at the site.

3.2 Background

There are various technologies being developed to integrate into microgrids. These technologies could replace or modify legacy spot backup diesel generators to allow them to interface with other generation sources instead of supplying emergency or critical loads, improve power electronics to work on new control schemes when grid anomalies occur, and automate distribution switchgear for ring, zonal, or new distribution topologies. As these technologies are integrated into a system performance evaluation will be needed.

The study team collected data and anecdotal information during site visits to Department of Defense (DoD) bases and by speaking with energy managers. The resulting broadly themed questions arose: (1) would microgrid systems actually be more available than spot or centralized diesel backup; (2) which microgrid configurations would provide maximum availability; and, (3)
which set or subset of technology investments would provide the greatest benefit in microgrid availability.

Microgrids' increased complexity may likely reduce their availability, especially under adverse environmental conditions, but the full system may nonetheless be more reliable and available than any individual subsystem. Additionally, subsystems within a microgrid could operate on a more regular basis than sitting idle for extended periods of time due to no emergencies which could decrease the chance of generation resources not starting and improve the systems availability.

This work answered the questions by: (1) establishing a generic framework for inputting characteristic information about a microgrid; (2) evaluating various microgrid topologies and configurations; and, (3) determining and comparing the reliability, but more specifically, the availability, of a microgrid to serve the systems loads.

The work was completed within MIT-LL’s Microgrid Living Laboratory project, which is currently developing a microgrid at MIT-LL. This microgrid will demonstrate best practices, provide a testbed for new energy security concepts, and reduce the MIT-LL’s energy footprint.

3.3 Scope

This study focuses generally on sections of the grid with an average load of 1 to 50 MW which could include, but is not limited to DoD bases, college campuses, and industrial parks. It did not evaluate the transmission or high voltage distribution systems (greater than 69kV) that supply a site, though the information gathered from developing the simulation’s code could be leveraged to integrate this study’s results with availability metrics for the bulk power system as a follow-up project.

An analysis of power generation, distribution, and loads using common parameters such as average or peak power can be used to establish a baseline for result comparison. Various generation sources such as cogeneration/combined-cycle natural gas power plant, solar photovoltaic, wind, diesel, and other generation sources, can be considered. Energy storage as a steady supply to the load was excluded, though it could supply necessary energy to the load during a transition from being grid powered to completely islanded. The power system’s distribution network was divided into the status quo schematic, proposed ring, and proposed zonal topologies. Since most of the existing infrastructure’s circuits and switchgear are near the
emergency circuits and technical solutions exists for operating multiple generators together, then it was assumed that the existing equipment (backup generators, transformers, etc.) could be modified and reconfigured to supply the main circuit instead of just the emergency or critical loads.

A literature review of the previous analyses conducted on the reliability and availability of electric power distribution systems, distributed generation systems, district heating and cooling systems, and backup diesel generators was also considered. This included both theoretical and engineering analysis of specific microgrid deployments. This literature review guided the development and improvement from the existing state of the art. The code and simulation provide several key advantages that will be discussed in further detail.

3.4 Analysis Tool

Excel and Matlab were used to develop a software tool that can process measured or estimated electrical parameters and evaluate various energy security solutions for power flow and availability. This software can also run existing and modified power distribution, generation, and storage assets. Existing spot backup diesel generators and a planned future cogeneration set of 10 MW were the main types of generation used in the case study. The systems performance was simulated under various adverse conditions, such as a generic N-1 conditions or threat-specific damage conditions. These damage conditions could be attributed to primary threat categories: severe weather, human error, and/or intentional attack.

3.4.1 Psuedocode of Generic Analysis

A flowchart of the software tool is shown Figure 23. First, data is entered into an Excel document, which includes 15 sheets for this simulation tables 1 and 12 are the most important (a list of relevant sheets to this case study is included in the Appendix). The user can scale the system to any size of nodes and lines by adding a new row of information. As the system grows in size additional computational capabilities may be necessary. The framework is the scalable in power from Watts to Megawatts and base units (i.e. Watts, Volts, Amps, etc.) are used. The system has been tested only in the range of the scope of this project. Matlab is used to read the excel document and import the relevant information needed for the analysis. Comments and additional information of parameter variables is provided in the Excel sheet. Matlab displays the power system information over the sites satellite image pulled from Google Maps via the API.
An AC power flow analysis is done to determine the power supplied and delivered, identify any overloaded busses or lines, and calculates the percentage of load served. Failures and adequate power is checked to validate the system and a tolerance for convergence is set. The resulting information is outputted via a .mat file and text in the Matlab command line.

3.4.2 Generic Framework for Microgrid Characteristic Information

The literature review resulted in the use of the IEEE Goldbook, IEEE STD 493-2007, IEEE Reliability Test System 1979 and 1996 to develop a generic framework for characterizing the system. These standards with insight from practical work experience at power
plants and on power system test-beds defined a basis framework for defining a generic power system.5,6,7

The data came from several sources. The electrical characteristics of the site such as the 13.8 kV one-line power distribution diagrams (see Appendix), power ratings of existing backup spot generators, and power usage data for most buildings via a data historian system (DataLINC and Pi Server). The site’s buildings established and monitored a network of power meters from various suppliers that interfaced to a server functioning as a data historian, called the PI Server. Additional data points were added continually. Access to the PI Server was created using DataLINC, a third party web-based interface that displays electricity, heating and cooling, and temperature parameters. This network schematic of the PI Server and meters is shown in Figure 24. Though the DataLINC system can read everything in the PI Server, it cannot output and download more than a few data streams at one time. This made analyzing the data of the site extremely difficult because more than 50 voltage and current points are needed. Access to the raw information on the PI Server was achieved, which allowed for more complete and better data analysis of the electrical parameters and benefit other energy projects.8

A separate server was setup by the MIT-LL Energy Initiative to manage the information. This server was only set up to capture electricity information from approximately two dozen meters at a potential rate down to one data point per second. Though the resolution of data is on the order of 5 minutes this is better than what is necessary for this study which is the hourly data to determine the peak demand of the year. This server is was not setup to be a comprehensive database of all the sites data because the system could not monitor all relevant metered points (buildings, switchgear, etc.).9

Once the raw data was accessed from the PI Server, a Virtual Machine (VM) was set up to leverage all the information collected by the PI Server. The Dot 19 subnet had many servers/devices asking for information from the meters. Some meters were being overloaded with request and the system was not operating as well as it could be. Once the VM was implemented reduced the clashing traffic pinging a subset of the electricity meters because it read the PI Server data historian instead of directly to the meter.
3.5 Application to the Case Study

Three types of test scenarios were developed for the analysis, though other topologies and configurations can be used. The setup and analysis on the existing, proposed ring bus, and proposed zonal configurations were done.

The system demand of the site was determined from the measured building data. Figure 25 shows the total real power and each of the three main lines (circuits) the over the past year ending on September 2014. The red dotted line represents the average and the maximum total power used. The power used for the analysis was 15.3 MVA at 14.2 MW which corresponds to the peak power usage over the year. The peak happened during the summertime. It should be noted that each of the main lines (#1387, #1388, and #1389) is a complete 3 phase circuit so there is a total of 9 physical power cables. The table in the appendix shows the rating of each of the 3 main circuits and parameter calculations.
Figure 25: Histogram of the Total Real Power used at the site over a year.

Figure 26 shows the site overlaid with the node number and main voltage of each building. Voltages above 480 Vac (red and green) have a step-down transformer to provide 480 Vac (green) or below. The numbers correspond to the bus (node) and the power lines are connected between two nodes via a straight line. Though the actual lines do not run in straight lines in reality it does not significantly affect the sites peak power flow, any unbalanced phases, or phase differences because the length of the lines are not long. This was validated by building data measurements on voltage, current, phase balance percentages, and etc. The easy identification of the bus number and line number allows the user to easily reconfigure (add, remove, or change connections) a given power system in a “connect the dots” approach. The code automatically updates to the new topology.
3.5.1 Case 0 and 1: Current Distribution (Spot Generation vs Central Generation)

This test scenario uses the sites existing power distribution architecture. This topology is most closely related to a radial topology. The spot generation uses the existing backup generators to supply the building loads. The central generation is located near the main feed line in the upper right corner. Figure 27 shows the connection topology. The three main feed lines are coming from a substation not shown in the image but located to the top right of the current...
frame. The ratings of each of the lines are 7.2 MVA, 7.2 MVA, and 10.2 MVA, and the appendix contains the calculations of their respective ratings.

![Diagram of Existing Infrastructure Connection Topology](image)

**Figure 27: Existing Infrastructure Connection Topology**

There were some planned changes since 2014, but the current topology as of summer 2014 was modeled. Case 0 and 1 in the section below will reference this Figure 27. The comparison section highlights which power availability numbers were calculated.

### 3.5.2 Comparison of Microgrids

The generally accepted intuition is that certain topologies (radial, ring, zonal, etc.) yield better or worse power availability due to factors such as prioritization of loads, increased interconnectivity, and placement of generation. Depending on the topology certain practical limits need to be imposed and can change the intuitive sense, and highlights why there is a need for a more rigorous analysis to compare different topologies on as close to equivalent test case.

A radial topology can result in a relatively good power availability given some constraints. The practical constraints for maximizing the availability is the highest priority loads should be near the top of the branches or generation should be connected directly to those loads. This will minimize the effect of a broken bus or line. If the total generation capability is less than
50% of the demanded load, then there is a significant probability that distributed or single generation will yield similar availability because different parts of the system may be powered based on location of the generation assets. A common intuition is that this topology has the worst power availability.

A ring bus topology can result in better power availability and can alleviate N-1 failures in theory. In practice there are limits to the theory for distributed or single generation. If the ring bus is small in loop distance, high enough in voltage, or large enough in line capacity, then the availability can be higher for a single generation, but is dependent on good placement of the asset. The addition of distributed generation can increase the ring size and availability. A significant constraint is that the upstream lines (lines closer to the generation) carry more current than other parts of the ring. The ring bus topology has the common intuition of being better than a radial topology.

A zonal topology can result in the best power availability and can alleviate N-1 and N-x failures in theory. The main practical limit is increased cost due to adding more lines for the needed interconnections. Both distributed and single generation can leverage the increased interconnections to ensure availability. The common intuition is the zonal topology has the best power availability.

The output metric for comparison of the power availability is the percentage of load served and is calculated by the \( \frac{kV A_{supplied}}{kV A_{needed}} \). Table 3 highlights the key findings of the simulation for the different cases.

**Table 3: Comparison of Results**

<table>
<thead>
<tr>
<th>Case</th>
<th>Failure of Main</th>
<th>Grid Failure (3 of 3 Main Lines)</th>
<th>with Failure of</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 no generation (with 7.2MVA)</td>
<td>70.17% 53.34%</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>0 no generation (with 10.2MVA)</td>
<td>123.51% 106.60%</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>1a current distribution (spot with 7.2MVA)</td>
<td>214.84% 103.39%</td>
<td>44.23%</td>
<td>B - Building (#12) 46.32% B Building Line 46.32%</td>
</tr>
<tr>
<td>1b current distribution (1 source with 7.2MVA)</td>
<td>224.05% 103.39%</td>
<td>46.70%</td>
<td>B - Building (#12) 46.32% B Building Line 46.32%</td>
</tr>
<tr>
<td>2a ring bus (spot)</td>
<td>n/a n/a</td>
<td>45.83% S Building</td>
<td>39.28% J to C Bld. Line 39.11%</td>
</tr>
<tr>
<td>2b ring bus (1 source)</td>
<td>n/a n/a</td>
<td>31.10% Switchgear 3</td>
<td>25.28% Sw. to E Bld. 25.28%</td>
</tr>
<tr>
<td>3a zonal (spot)</td>
<td>n/a n/a</td>
<td>46.32% S Building</td>
<td>46.32% S to V Bld. 46.32%</td>
</tr>
<tr>
<td>3b zonal (1 source)</td>
<td>n/a n/a</td>
<td>43.89% Switchgear 1</td>
<td>46.32% Sw to E 46.32%</td>
</tr>
</tbody>
</table>

**3.5.2.1 Case 0: Current Distribution without Generation**

In the current infrastructure topology of the site there are three main lines (7.2 MVA, 7.2 MVA, and 10.2 MVA) that provide power to the site. If a failure of one or two of the main lines
occurs and there is no generation (spot or single source), then widespread outage up to approximately 50% could happen. The range of power availability without generation (spot or single source) for one of three lines failing is 70.17 to 123.51%. This large range is due to whether the 10.2 MVA line is in service. If two of the three lines fail then the range is 53.34 to 106.60%. The critical buses and lines of this system are the main switchgear and lines coming into the site.

3.5.2.2 Case 1: Current Distribution with Generation

In the current infrastructure topology with site generation there is 7.075 MVA of generation available corresponding to approximately 46.32% of the peak site load (15.3 MVA at 14.2 MW in the summertime). The current spot generation is co-located next to the load and in most cases is manually transferred to power an emergency load. It is assumed that these existing spot generators can operate together and serve non-emergency loads because modifications to allow generators to parallel, reconfiguring the loads connected, automatically switching from grid to on site generation, equipment protection, and etc. are issues not mostly limited by technologic barriers. This type of generation source is considered distributed generation. If one or two of the main lines fails, then above 100% power availability is achieved because site generation can compensate for the reduced grid power capability. The simulation shows that spot and single source generation yielded the same results. This is to provide a transition range from the partial failure of the main lines to an isolated system. If the power grid fails or the site is islanded, then approximately 46.32% of the load is able to be served.

3.5.2.3 Case 2: Ring Bus Configuration

In the ring bus topology the existing voltages and line capacities were used with the same generation as the other cases. In the single source case the central plant is located near the main switchgear near the upper right. The power availability shown in the table was less than the current infrastructure topology due to the practical constraints of voltage and current capacity. The voltage in some of the ring sections was 4160V instead of 13.8kV because of building transformers. The line capacity was not sufficient enough to carry the increased current because the upstream lines (lines closer to the main switchgear) are rated to handle a subset of the power coming in. It should be noted again that the maximum on site generation is approximately 46%. In the spot and single generation cases with no additional lines removed resulted in 45.83% and
31.10% availability, respectively. This lower value than the maximum is due to additional line losses at the voltages less than 13.8kV due to higher currents than case 1. In the distributed generation subcase, the critical bus was S Building (largest single building load at approximately 2 MVA with the second largest generator at 1MVA) and the critical line was from J to C building which isolates several generators and increases line losses due to the 4160V instead of 13.8kV. In both of these cases kVA supplied is reduced, and therefore the power availability drops to approximately 39%. In the single generation subcase, lines failed due to the increased current demands. The central source connects to main switch gear buses. The removal of one of the three busses or one of the two lines results in approximately 25% availability. In addition, the single source is not able to provide enough reactive power to ensure voltage stability even though the machine could output more real power. The simulation shows that the ring bus loop is too long, the 4160V instead of 13.8kV creates significant amount of current, and the some of the lines are not able to carry the additional current needed. This results in the ring bus being worse than the current distribution in all cases.

3.5.2.4 Case 3: Zonal Configuration

The zonal topology assumed the same conditions as generation placement as case 2 except for a change in the wiring scheme. The power availability shown in the table was equivalent to the current infrastructure topology of case 1 due to the good interconnection of the loads to each other. In the distributed generation subcase the key difference between the case 1 and zonal is that the critical bus is S building (2MVA load) instead of B Building (feeds 5MVA load). This illustrates that increased interconnection results in mitigating the critical branches that may affect multiple buildings. The critical line was S to V building which makes the power routed differently out to the far buildings. In the single source subcase the critical bus and line is near the source itself (Switchgear 1 and Switchgear to E building); however, the interconnection allows power to be routed around any removed lines. It should be noted again that the different parts of the site were powered up, even though the power availability of the zonal topology was equivalent to the current distribution of case 1. The simulation can show how the zonal topology is better than case 1 when on site generation is increased above 50%.
3.5.3 Site Specific Recommendations of Infrastructure Change

In the current infrastructure topology without generation, there are a couple of recommendations to increase the power availability that can be inferred from the simulation. If the 7.2 MVA main lines were increased in capacity to 10.2MVA then this would ensure above 100% power availability when power from the grid is capable of handling the load. The site is working with the local utility to accomplish this and should be completed by 2018. This recommendation ensures 100% power availability when the power grid is present, but provide little to no power availability when the grid is down.

In the current infrastructure topology with site generation, there are a couple of recommendations to increase the power availability. The existing capacity of site generation would need to be increased because less than 50% of the site could be islanded. If generation was increased, then some line capacities need to be increased and the choice between distributed versus single generation, becomes extremely important. The simulation can run hypothetical cases with varying amounts of generation and illustrate the power availability. The table illustrates for the current distribution that both spot and single source yield the same availability, but this is unique to the current conditions. When a critical bus or line is removed the systems has the same availability because different parts of the site become powered, therefore a prioritized list of loads (buildings) would need to be created to account for this factor. In addition, B Building bus and line was determined as a critical piece and feeds several other large buildings totaling approximately 5MVA. Mitigation of how critical B building is can be achieved by connecting some of the buildings to a different building and/or equipment hardening via a third set of lines. These recommendations increase the power availability when the power grid is not present, but topology and generation placement need to be determined.

In the ring bus topology, significant investment would be needed to increase the power availability from the simulated outcome to equivalent power availability of case 1, then to reliable N-1 failure, and then to better power availability than case 1. Transformers capable of 13.8kV instead of 4160V would be needed to reduce current demand and could leverage the existing cable ampacity ratings rated for high enough voltage. Higher capacity lines would be needed in some places to carry the larger current needed. The use of distributed generation would reduce the effect of the long ring bus loop, but if a single source was used the placement would
be better if it was located in a more central spot. A ring bus would not be ideal, but could be an intermediate step to another topology.

The zonal topology resulted in the best results of the cases, and a couple of recommendations not mentioned previously could increase the power availability. Several of the buildings have multiple branch circuits. If these different building branch circuits were connected to various other buildings, then this would increase the interconnection and would allow for the better routing of power, and could reduce the need for additional wires. The key to leveraging the zonal topology advantages is to have an interconnected/mesh scheme between large or critical loads.

3.6 New Microgrid Reference Model

A new power system IEEE Reference model is being adopted from the anonymized physical radial feeder with 10 MVA nominal power, 10 buses and 25 lines, 10 load profiles, and a 1 and 4 MVA generator. The 19 relay/monitoring points and 2 other DERs (3.5 MW solar, and 4 MW 0.5MWh battery) were simulated. Data sheets on the physical generators were collected and sub-minute monitoring of the physical load’s power were installed. This information was used to develop the Matlab SimPower Systems models of the power system, load profiles, and generators and was released with other models from MIT Lincoln Laboratory.
Figure 28: The 4.5MW feeder system called Sheriff.
Figure 29: The Sheriff and Banshee power systems. These real sites were anonymized and modeled to create a digital twin of the real world power system. It is being used as a new reference feeder.
Chapter 4: Microgrid Modeling and Control

This cost to deploy physical hardware onto power systems can be capital intensive, time consuming to install, and laborious to troubleshoot. A lower cost solution with increased test coverage and validation to real world equipment will be described. This solution incorporates the development of a controller hardware in the loop platform.

4.1 Framework

A generic framework for describing the different model and controls level will be used. This framework is agnostic of controller bandwidth, computation time, or generation type. The lowest layer is the electromagnetics and electromechanical, and comprises of the device physics, machine characteristics, or the physical structure or components. A few examples will be provided to give a clearer illustration, but it is not to be considered an exhaustive list. Examples of the electromagnetic and electromechanical layer: 1. the electrical parameters of the wire such as impedance, capacitance, inductance, and power capacity. 2. the physical parameters of a machine such as the physical dimensions, inertia, and rotational ratings. 3. the electromechanical parameters of a device such as on/off times, interruption current, voltage breakdown, and number of operations. The next layer up is the primary control(s) layer, and has at least the goal of equipment protection by controlling the electromagnetic or electromechanical layer. Examples of the primary control layer: 1. the governor of the machine to protect it from overspeed 2. the automatic voltage regulator of a machine to ensure that it does not exceed electrical ratings 3. dedicated printed circuit boards for power electronics to guard from shoot through or thermal runaway. The secondary control layer is mainly a forcing function to achieve a desired goal and may control or bias the primary controller and/or control the electromagnetic and electromechanical layer. Examples of the secondary control layer: 1. controlling the real power (P) and power factor (pf) 2. controlling the voltage (V) and frequency (f) 3. implementing a novel new controls scheme. The electromagnetic and electromechanical, primary controller, and secondary controller are typically co-located. The final layer is the tertiary control which has a higher level perspective and goal of controlling one or more pieces of equipment that have the other layers. It is common for the tertiary control to perform its actions via communications protocols to include but not limited to RS232, RS 485, TCP/IP over Ethernet, Modbus, and CAN.
The elements of the following sections will be organized into electromagnetic and electromechanical, primary control, secondary control, and tertiary control layers. However my contributions will only be listed for the relevant sections. It will include elements of control loop time, the functionality, and other relevant parameters.

4.2 Environmental Control Units to Smart Loads

Environmental control units are one of the largest loads on forward operating bases and have very basic operation. The goal of this project was to take these basic operation units and convert them to smart loads. The follow-on work has been with Professor Leeb and Spencer Shabshab at the Base Camp Integration Lab. Figure 30 shows an example of the environmental control unit for the military.

![Image of environmental control unit](figure30.jpg)

Figure 30: Environmental Control Unit for the military. This is the third generation and is designed by HDT. The units used were tested at MIT Lincoln Laboratory and the Base Camp Integration Lab in Western Massachusetts.

4.2.1 Electromagnetics and Electromechanical

The F100-60K ECU provides heating, cooling and ventilation of the enclosed space created by the deployed shelter. Its electrical connection is 208VAC, 60 Amp, three-phase 60 Hz and has nominal 60,000 BTU/hr. The ECU is designed to provide heating or cooling over the ambient temperature range of -50°F to +135°F Fahrenheit. The ECU is equipped with a local Operator Control Panel with a mode selector switch to set the operating modes between Off, Vent (1.56 kW), Cool (8.13 kW), Heat (10 kW). Temperature is regulated and set by a return-air
thermostat. The additional parameters of the machine can be determined by refereeing to the manual. [6]

4.2.2 Primary Control
The primary control was not modified for this work and all protection of the equipment such as over temperature, out of phase, over current, and pressure alarms were still performed by the in unit controller. The designed printed circuit board and Arduino microcontroller provided addition interlocks and protection. Monitoring and diagnostics was design and provided for two previous ECU equipment models.

4.2.3 Secondary Control
The secondary controller was originally designed using and Arduino microcontroller to perform the following operations.

- **Mode and Setpoint Control**: The ECU mode selection and temperature setpoint could be controlled locally or remotely. This allowed for performance increases to the ECU by reducing the temperature deadband, reducing energy consumption, and allowing for situational awareness of the on the ground state.

- **Temperature Monitoring**: Various ECU models have either an RTD100, thermistor, or type K thermocouple for monitoring and controlling the temperature, and is typically located at the output of the unit. The designed controller has the ability to monitor the local temperature and regulate control of the unit.

- **Diagnostic and Maintenance Monitoring**: Analog to digital converters were used to monitor selected points on the ECU to include but not limited to 1. high pressure and low pressure of the cooling loop 2. voltage out of phase 3. previous maintenance checks 4. over temperature, and 5. system faults.

- **Other Control Signals**: Various ECU models have either 24Vac, 24Vdc, or 5Vdc logic. Digital to analog converters were used to generate different control signals that could be used to provide additional level of control of the unit.

This work helped to develop the standard for the ECU military device model for control and diagnostics. In addition, Rick Burbage at MIT LL and I worked on creating a ECU equipment model in Matlab Simulink. He was able to take the information we collected in the field and create a more accurate plant of the ECU unit. Spencer Shabshab and I have been able to
miniaturize and improve the functionality of the control board. The first version in 2012 had an installation profile of 2592 in.\(^3\) (18in. x 18in. x 8 in.) and was placed near the ECU. The 2017 version is 144 in.\(^3\) (12in. x 3in. x 4in.) and can be placed inside the ECU. Figures 31 and 32 shows the latest revision of the control board and it being installed in the ECU.

![Diagram of control board capabilities](image)

**Figure 31:** ECU retrofit controller version 3 with capabilities highlighted.

![Installation of controller in ECU](image)

**Figure 32:** Installation of the ECU retrofit controller version 3 into an ECU unit.

### 4.2.4 Tertiary Control

The tertiary control is performed by a laptop computer running Matlab. The goal was to reduce if possible the overlap of multiple ECU units. This was achieved by the developed
algorithm to ensure that the lowest number of ECU were turned on and tested at the Base Camp Integration Laboratory. The Matlab code has been posted to Github and is called system scheduler. Figures 33 and 34 show the uncontrolled and controlled ECUs.

![Figure 33: Four uncontrolled ECU units turning on and off whenever local heating is needed.](image)

![Figure 34: Four controlled ECU units to maintain the heating setup and reduce the runtime overlap when possible.](image)
4.3 Intelligent Power Distribution (IPD60)
The military legacy power distribution equipment is called PDISE. The work done was to engineer for the military and intelligent power distribution systems rated for 60 amps to make any "dumb load" smart. After the equipment was designed and test the unit and technology was transfer to Wiley to be manufactured and field deployment. Figure 35 shows the intelligent power distribution 60A unit that fits within the existing PDISE form factor, maintains the 2 man carry, and increased the monitoring and diagnostics capability when connected to a load or networked to form the up to 1MVA power system.

4.3.1 Electromagnetics and Electromechanical
An electromagnetic and electrometrical model was developed by other team members of the group based on the design that I developed.

4.3.2 Primary Control
The primary control and monitoring board hardware was designed, tested, and integrated into the IPD 60. The actual software coding and communications protocol was developed and implemented by Gabe Ayers at MIT LL. This work was later transition to Peter Klein at MIT LL.
4.3.3 Secondary Control

The secondary control was not a design requirement by the sponsor, but a simulation secondary controller was modeled in Matlab Simulink.

4.3.4 Tertiary Control

The tertiary control was designed by a colleague on the project.

4.4 Diesel Generators

The two simulated Caterpillar diesel generators in the system correspond to a 1000 kVA (CAT 32) and a 4000 kVA (CAT C175-20), operated at nominal voltages of 480 V and 13.8 kV, respectively Figure 39 [3]. Figure 37 shows the interfaces of the Woodward easYgen controllers with the simulated 1000 kVA generator and 4000 kVA generators. The Woodward communicates to the vendor microgrid controller via a Modbus interface. However, all communications, such as generator commands and (voltage/frequency) set points, are sent from the Woodward controllers to the Opal-RT simulated system using digital I/O channels. Further discussion on the Woodward and its topology is provided in the appendix.

This is the work on the 0.4MW to 5MW class diesel generators and system identification. The 1 MVA and 4 MVA diesel generators were modeled. The 1 and 4 MVA synchronous generators had modeled power system connections, machine parameters, and excitation system (governor and automatic voltage regulator) that were tuned for the respective generator. These models were connected to a simulated and physical secondary controller. The unit test of the model consisted of emergency startup, synchronization of the generator or mains circuit breaker, changes in real and reactive load, and shutdown. The 1 MVA diesel engine that was monitored and characterized by non-intrusive load monitoring.
Figure 36: 1 MVA, 480Vac, 60 Hz, 3 phase diesel generator that was monitored and characterized for modeling.

An example of the control diagram is shown in Figure 37. The orange box is the physical controller, the blue box is everything in simulation, and the green box was the developed interface box with the proper signal conditioning.

**HILLTOP Device Controller Integration: Brassboard**

Figure 37: Diesel generator control diagram and model.
4.4.1 Electromagnetics and Electromechanical

The electromagnetic and electromechanical model used the pre-built Matlab Simulink R2011b and R2013b prime mover machine and generator models. The nameplate ratings, equipment datasheets, startup and shutdown tests, and estimation of unknown quantities based on measurements that could be taken were done to increase validity of the prime mover machine and generator models. Figure 38 shows the comparison of the SI fundamental, PU fundamental, and PU standard models of the synchronous machine.

![Figure 38: Synchronous machine parameters for three different model types: SI Fundamental, PU fundamental, and PU standard.](image)

<table>
<thead>
<tr>
<th>Manufacturer / Model</th>
<th>1 MW Genset</th>
<th>4 MW Genset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rating (kVA)</td>
<td>1,000</td>
<td>4,000</td>
</tr>
<tr>
<td>Power Factor</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Voltage (V)</td>
<td>480</td>
<td>13,800</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Speed (RPM)</td>
<td>1800</td>
<td>1800</td>
</tr>
<tr>
<td>Minimum Output Power</td>
<td>25kW</td>
<td>100kW</td>
</tr>
<tr>
<td>Startup Time</td>
<td>&lt;10 sec</td>
<td>&lt;15 sec</td>
</tr>
</tbody>
</table>

**Figure 39: Machine parameters of the 1 and 4 MVA diesel generators.**

4.4.2 Primary Control

The primary control includes the development of a governor and automatic voltage regulator (AVR) model. The previous state of the art included the IEEE standard 421.5-2005...
which is comprised of several excitation system types, the MATLAB SimPowerSystems Hydro Quebec toolset R2011b which had a rudimentary DC1A excitation system example, and Mirjana Marden at MIT LL who improved the primary controller model and developed a simulated secondary controller. The previous work was built upon to take the non-field tested simulation (pure simulation in Matlab) to a more valid representation of the physical controllers by instrumenting a 1 MVA diesel generator with high speed non-intrusive monitoring at 8kHz sampling frequency which monitored the AVR control of the synchronous machine’s field voltage, and the governor’s regulation of the diesel engine’s throttle to control frequency. A system identification methodology was performed. The excitation system of 14 generators were studied during their monthly maintenance and run tests, which determined that a DC4B excitation system was most common for generators from 0.1 to 2.5 MVA. The appendix shows the different Excitation system types. The block diagrams of the model with equations can be seen in figures 40 and 41. The model was converted from the rudimentary DC1A to a more detailed DC4B excitation system as shown in Figure 42.

Figure 40: Governor model and equations.
Figure 41: AVR and Excitation system model.
Figure 42: System identification of the common excitation system, development of a new model, and validated user parameters for a DC4B Excitation System.

Figure 43: Matlab Simulink models developed.

The first working primary controller model (called Governor and AVR v1) when integrated with the simulated secondary controller would startup, stabilize at a power rating, be within voltage and frequency ratings, and would shutdown. Therefore, the model seemed to correct. The unknown unknown(s) at the time that made this V1 model not correct were seen when the physical secondary controller was connected, and it became clear that the simulated
primary control needed to match reality. Signal conditioning from the secondary controller, protection logic of the primary controller, governor and AVR model parameters, and tuned primary controller PID parameters were needed in order to achieve the physical controller working with the simulated secondary controller. When this milestone was achieved the model was saved as Governor and AVR V6. Figure 44 highlights the difference between V1 (left) and V6 (right). The test sequence had the diesel generator start from an initial stop, stabilize, and shutdown. In the V1 model it is clear that voltage phase A to neutral (Van) goes from 0 Vrms to stabilizing at 277 Vrms (391 Vpk) then decays back to 0 Vrms. The terminal voltage follows a similar characteristic as expected and was converted to a per unit value. However the mechanical speed took an abnormally long time to decay compared to data collected from the non-intrusive load monitoring. One argument that could be made is that the engine resistance, shaft inertia, and/or friction and windage factors were incorrect; therefore, these values were estimated based on measuring the 1 MVA diesel generator and checked to the model. There was not a significant difference in the results. A deeper dive into the Matlab Simulink model was done, but again no issue was found. The V6 model corrected issues in the primary controller model based on additional data from the physical generator’s excitation system, and the same test sequence was performed on the V6 model. The phase A voltage to neutral, terminal voltage, and mechanical speed matched each other and decayed to zero within the same time.
Figure 44: Version 1 (left) of the primary controller model that only worked with the simulated secondary controller, and Version 6 (right) which worked with both the simulated and physical secondary controller.

The changes from V6 (old) to V9 to the 2017 version where only changes to the parameters and not fundamentally the models. The changes to the parameters used are listed in Table 4.
Table 4: Governor and AVR parameters.

<table>
<thead>
<tr>
<th>AVR</th>
<th>Original</th>
<th>V1</th>
<th>V6</th>
<th>V9</th>
<th>2017</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tr [s]</td>
<td>0.02</td>
<td>0.002</td>
<td>0.002</td>
<td>0.02</td>
<td>0.02</td>
<td>Low pass filter time constant</td>
</tr>
<tr>
<td>Ka []</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>Regulator gain</td>
</tr>
<tr>
<td>Ta [s]</td>
<td>0.02</td>
<td>0.002</td>
<td>0.002</td>
<td>0.02</td>
<td>0.02</td>
<td>Regulator gain constant</td>
</tr>
<tr>
<td>Ke []</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Exciter</td>
</tr>
<tr>
<td>Te []</td>
<td>0</td>
<td>0.00000001</td>
<td>0.0000001</td>
<td>0</td>
<td>0</td>
<td>Exciter</td>
</tr>
<tr>
<td>Tb []</td>
<td>0</td>
<td>1e-12</td>
<td>1e-12</td>
<td>0</td>
<td>0</td>
<td>Transient gain reduction</td>
</tr>
<tr>
<td>Tc []</td>
<td>0</td>
<td>1e-12</td>
<td>1e-12</td>
<td>0</td>
<td>0</td>
<td>Transient gain reduction</td>
</tr>
<tr>
<td>Kf []</td>
<td>0.001</td>
<td>0</td>
<td>0</td>
<td>0.001</td>
<td>0.001</td>
<td>Damping filter gain</td>
</tr>
<tr>
<td>Tf []</td>
<td>0.1</td>
<td>1e-12</td>
<td>1e-12</td>
<td>0.1</td>
<td>0.1</td>
<td>Damping filter time constant</td>
</tr>
<tr>
<td>Efmin</td>
<td>-5</td>
<td>-5</td>
<td>0</td>
<td>0.5</td>
<td>0.25</td>
<td>Regulator output limits</td>
</tr>
<tr>
<td>Efmax [pu]</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>6</td>
<td>Regulator output limits</td>
</tr>
<tr>
<td>Kp []</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Regulator output gain</td>
</tr>
<tr>
<td>VfD [pu]</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Terminal voltage initial value</td>
</tr>
<tr>
<td>VfD [pu]</td>
<td>1.4273</td>
<td>1.4273</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>Field voltage initial value</td>
</tr>
</tbody>
</table>

The startup and shutdown of the physical generator was during the monthly maintenance test. The data collected on the machine was originally from the DataLINC system which comprised of SquareD and Schneider meters that had a recording resolution as fast as 1 Hz. It was falsely assumed that the logging and data historian was at this 1 Hz resolution meter setting because when data was pulled and downloaded the data had a timestamp. It was not until the high speed data monitoring was added that the DataLINC information was averaged and interpolated between meter readings to provide the desired resolution. Figure 45 shows a table and plot of the two monitoring systems. The NUC computer and non-intrusive monitoring system was used for model development.
Table: Phase Min (sec) Max (sec) Mean (sec) St. Dev. (sec)

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DataLINC</td>
<td>Startup</td>
<td>9</td>
<td>62</td>
<td>37.9</td>
</tr>
<tr>
<td></td>
<td>Shutdown</td>
<td>30</td>
<td>92</td>
<td>57.8</td>
</tr>
<tr>
<td>NUC (NILM)</td>
<td>Startup</td>
<td>3.95</td>
<td>7.76</td>
<td>5.68</td>
</tr>
<tr>
<td></td>
<td>Shutdown</td>
<td>21.14</td>
<td>27.38</td>
<td>23.71</td>
</tr>
</tbody>
</table>

Figure 45: The startup and shutdown characteristics of the physical 1 MVA diesel generator after 11 runs over 3 months.

Figures 46 and 47 shows the old (V6) and new (2017 version) of the primary controller. The 2017 version falls within the standard deviation of the average startup and shutdown characteristics. One arguable point is that some dynamics such as the startup bump at 5.5 seconds (240Vac) and slight overshoot at 7.2 seconds (285Vac) are not modeled. This phenomena was due to the physical primary controller on the diesel generator. The goal is to have a generalized not one specific model of the primary controller that the secondary controller and microgrid controller can command. The feedback loops of these controllers are much slower and would not actually register these dynamics. The 2017 version primary controller was within the standard deviation of the physical primary controller which is more than valid for this application.
Figure 46: Startup characteristic of the physical generator (non-intrusive high sampling speed), DataLINC (low sampling speed), old model (V6), and new model (2017).
4.4.3 Secondary Control

The secondary controller was a physical generator controller (i.e. Woodward Easygen 3500). The use of physical controllers is a major benefit of controller hardware in the loop for the increased validity compared to pure simulation and order of magnitude lower cost of the controller compared to deployment of the entire equipment. Figure 48 shows the Woodward generator controllers integrated into the HILLTOP platform.

Figure 47: Shutdown characteristic of the physical generator (non-intrusive high sampling speed), DataLINC (low sampling speed), old model (V6), and new model (2017).
The voltage and frequency set points of the governor and AVR are adjusted / biased by the Easygen 3500. The adjustments of voltage and frequency set points allow for synchronization and control of real and reactive (by power / power factor control) power can be commanded. Two independent low-latency control inner-loops, on the order of milliseconds, are used to regulate output voltage and output frequency. While these two loops are controlled separately, their effects are coupled. Say, when the AVR increases voltage it will cause the generator frequency to drop, thus the governor will have to increase power to maintain its frequency set point. Likewise, if the governor increases power, then the AVR will need to compensate to maintain voltage. Force functions such as frequency droop, voltage droop, and synchronization, as well as other refinements to power quality are implemented. When the equipment is a new commission, then the generator manufacturer typically tunes these two control loops over a variety of operating conditions to ensure stability and a quick response to perturbations. However, when only the generator controller is purchased it is expected that the owner of the
unit will correctly setup the almost 4,000 parameters/registers which is an 856 page manual (reference 16) in the case of the Easygen 3500. Figures 49 and 50 show the user interface for the Easygen 3500, and this was done for two different generators.

Figure 49: Woodward Easygen 3500 programming and monitoring interface.
The secondary controller was setup to allow the tertiary controller to communicate several protocols to which included Modbus RTU, Modbus encapsulated in TCP/IP, CAN, and CANOpen via an Ethernet to DB-9 for RS232 and RS485 communication.

4.3.4 Tertiary Control

The tertiary control is done by the third party vendor’s microgrid controller. Advisement on how to control the diesel generator was provided by an Interface Control Document (ICD) developed for each annual symposium. A communications protocol survey was done with third party vendors. The result was that all supported at least Modbus, therefore this was the main communications protocol used.

4.3.4.1 Matlab GUI and Modbus Driver

A Matlab GUI interface that could control different relays and show monitoring points of the test feeder was developed by Aidan Dowdle (MIT LL summer intern and now MIT Graduate Student). The GUI interface was modified and further developed for use to control the two generators, additional relays, and provided a way to develop device unit tests. Figure 51 shows the GUI developed.
Matlab did not have a driver for Modbus over TCP/IP communication. A internet search was done and the results were 2 programs that did not work except for the very specific device they were designed to be used with. A generic Matlab Modbus over TCP/IP driver was developed. It has been tested to work with the most used function codes of read single register, write single register, write multiple registers, and read multiple registers. This generic code has been tested with 3 different physical controllers and was used to validate the Modbus protocol of other HIL Platforms. It has been posted to Github for others to use and improve.

### 4.5 Inverter Controller (Battery and PV)

A Battery Energy Storage System (BESS) and PV array were modeled and integrated into the controller hardware in the loop platform. Physical inverter controllers from a power electronics company called EPC Power were used after a survey of power electronics manufacturers. Their 60 kW converter/inverter can be used in a variety of configurations from DC/DC to AC/DC to DC/AC. Each module can be paralleled to increase the power capability from 0.2MW to 1.5MW. For this application they operated at nominal voltages of 480 Vac, 60 Hz, and 1.5 MVA rating. The EPC Power inverter communicates to the vendor microgrid controller via a Modbus or CAN interface, and the EPC inverter is connected to the Opal-RT simulated system using digital I/O channels for the gate drive, monitoring, and protection signals. The unit test of the models consisted of startup, standalone operation of controlling
voltage and frequency, synchronization to a generator or grid, changes in real and reactive power, and shutdown. Figure 52 shows the EPC inverter's progress from equipment to integration into the CHIL platform.

**CHIL Integration – EPC Power Inverter**

![Image of CHIL Integration – EPC Power Inverter]

**Figure 52:** EPC Power inverter used for the battery and PV modeling.

The main challenge for the development and integration of power electronics into the CHIL platform was the computation needed for an accurate solution within the specified time step of the real time simulator. This time step is a user defined variable that is ideally set to a value that the results each time step are faster than the controller loop. The realistic limits of the time step have to factor in model complexity and the number of computations needed to provide an accurate solution. At the end of the time step, if the computation is still processing, then an overrun occurs and the resulting solution is inaccurate.

4.5.1 Electromagnetics and Electromechanical

The electromagnetic and electromechanical model for power electronics can be more than an order of magnitude faster than the electromagnetic and electromechanical model for the
diesel generator because of the fast transition time of solid state devices. Since this model is much faster the control loop response time of the primary and secondary controllers will need to be faster, too. Figure 53 illustrates the time step / frequency range of signals to the CHIL. A time step of 100us (10kHz) was chosen for the 2017 symposium system model and the EPC inverter gate drive signals operated at switching frequency of 5kHz. The Nyquist theorem states that if a signal is sampled greater than twice its frequency, then the samples can be used to recreate the original signal. To achieve this from a physical system is not an easy task and certain conditions apply, however this was done and the EPC inverters were integrated into the CHIL platform.

- **Microgrid controller HIL simulates in real-time at sub-cycle timescales**

![Diagram showing time steps and frequencies](https://example.com/diagram.png)

**Figure 53:** The CHIL platform for the 2017 symposium was operated at a time step of 100us (10kHz). The EPC inverter gate drive signals were operated up to 5kHz (200us) and had double update rate capability which sampled every 100us (10kHz).

The most important component of this model was the computation speed to sample the gate drive signals, determine the state of the solid state devices, and output the correct waveform representation back the controller. Several Matlab Simulink toolsets were explored to include but not limited to SimPower Systems, SimPower Electronics, and SimDrives. The integration results from these toolset were failures due to either not being able to be compiled onto the OPAL RT realtime platform, the resulting computation taking longer than the time step which caused...
overruns, the model output not accurate to correctly model all states, the delay time being to long between the input signal to the output signal, or the THD of the output to large. Though the signal results from these efforts were failure the learning of what not to do given reasonable hypotheses was invaluable. Ultimately, the OPAL RT Real Time Events (RTE) toolset and their corresponding power electronics blocks were utilized with significant support from the OPAL RT technical team to achieve the desired results.

The OPAL RT RTE events toolset allows for signal transitions that happen between time steps to be seen and processed, though there are some limitations. The RTE events semiconductor models were parameterized and connected to the gate drive signals for all three phase of the EPC inverter controller. Figure 54 shows the LCL filter, gate drive block, and contactor block which make up this layer of the model.

![Figure 54: The electromagnetic and electromechanical model of the EPC inverter for the BESS.](image)

The battery and PV models were modified and improved after a survey of prior work was performed. The prior work showed that Chris Smith at MIT LL had a basic battery, PV, and inverter model that was used in the 2015 symposium, Matlab SimPower systems had a battery model, and Matlab Simulink in collaboration with Hydro Quebec had developed a large scale PV model. After troubleshooting the battery, PV, and inverter model developed at MIT LL and fixing several issues it became apparent that a more flexible and robust model was needed to integrate with the EPC inverter controllers. The Matlab SimPower battery was used and only its parameter values were changed after getting information from several battery manufacturers on reasonable ranges for medium voltage battery storage systems. The Matlab Simulink with Hydro Quebec PV model was used and modified to incorporate additional monitoring values and allow it to be scaled from a 0.2 to 5 MW rating. A perturb and observe controller for maximum power point tracking was developed in the case that the EPC power inverter could not provide this new
untested functionality at the time. The EPC inverter controller interface to the model can be seen in Figure 55.

4.5.2 Primary Control
The primary controller is performed by the EPC inverter controller and EPyQ is the user interface program to monitor and program the controller. As the battery and PV inverter model was developed and tested several revision were needed. There were 21 revisions to the firmware of the EPC inverter controller. Major and minor issues were found in the controller when testing and validating using the CHIL platform. An example of a major issue would be out of phase synchronization of the EPC inverter to communications commands not being registered by the controller. The equipment manufacturer was responsive to making these changes and data from the CHIL platform was used to troubleshoot the problem area. The value to the equipment manufacture was seen and they purchased a CHIL platform to improve product development and testing.

4.5.3 Secondary Control
The secondary control layer is also performed by the EPC inverter controller. The different operation modes such as grid forming (voltage and frequency control) and grid following (direct and quadrature current control), set point adjustments, and switching of relays are a subset of the functions that can be performed. Figure 56 shows the high level model of the secondary control.
Battery and PV Model

Figure 56: Battery and PV Model of the EPC Inverter.

The interface box is the piece that connects the physical to the digital. Figure 56 shows the rack and interface box developed. The electrical diagrams and supporting information are included in the appendix.
4.5.4 Tertiary Control

The tertiary control was done by the third party vendor's microgrid controller.

4.6 Site Loads

The load models used within the microgrid model were based on actual load profiles from the power system. This work was in collaboration with Raajiv Rekha at MIT LL and Matthew Backes (MIT LL summer intern and now an UIUC graduate student). A full year of historical load information (real and reactive power, 3 phase voltages and currents, and energy consumption) was collected. These dynamics of the realistic varying load were incorporated into the simulation model. The historical data provide the ability to distinguish between the different reactive and resistive loads. The load model developed used both reactive power loads, typical of industrial customers that have induction motors, and resistive loads, typical of lighting loads.
4.7 Controller Hardware in the Loop Platform

The CHIL platform development was a multi-year effort starting with the original project funding proposal co-developed with Erik Limpaecher. Several hardware in the loop manufactures were contacted and demonstrated their capabilities. The factors of the different platforms were weighted and the decision was made to choose the OPAL RT platform due to meeting the goals of lower cost, ability to expand to larger power systems networks, Matlab and Simulink support, and multiple communications protocols such as Modbus supported. The total equipment cost of the 2015 CHIL platform called HILLTOP was less than $275,000 and a block diagram is shown in Figure 58.

2015 HILLTOP Block Diagram

The 2015 symposium with approximately 125 attendees, 2 microgrid controller vendors, and 2 physical generator controllers implemented into the CHIL platform was a major success. Additional grants and follow-on funding was received and the platform was expanded to 7 physical controllers (1 diesel generator, 1 CHP generator, 3 substation relays, and 2 inverter controllers), a larger 15 MW microgrid digital twin developed, and more validated power
equipment models. The most recent symposium held in February 2017 attracted over 450 attendees and had a significant waitlist. The block diagram of the expanded CHIL platform is shown in Figure 59.

2016 HILLTOP Block Diagram

Figure 59: HILLTOP Block Diagram for the physical controllers integrated into the platform.

There are several other CHIL platforms that have come to the market since 2012, and each one has slightly different but overlapping capabilities. Depending on the users goals of doing testing with a HIL platform the price point can range from $10,000 to $500,000. In order to broaden the impact of this work, owners and the equipment manufacturers of the different HIL platforms have been assembled to port equipment models and copy the digital twin power systems model from the OPAL RT HIL platform to another HIL platforms. Figure 60 shows which efforts that have been done. A Github repository has been setup to provide collaboration.
HILLTOP Technology Transfer Efforts

Typhoon HIL

SEL SCHWEITZER ENGINEERING LABORATORIES

RTDS Technologies

Schneider Electric

OPAL-RT TECHNOLOGIES

San Nicolas Island

Figure 60: Technology transfer effort and contributions from other collaborators.
Chapter 5: Future Work

5.1 Microgrid Planning

The space of microgrid planning is continually improving. As satellite imagery becomes cheaper more efforts to use this additional information along with GIS services will be enabled. The Gridform code has been used on several microgrid siting projects and in 4 different countries. There are several improvements that can be made which are not listed in order of priority. The prediction accuracy of the final project cost is within ±10% and in the few cases that microgrids were deployed it was within ±5%. More sites would need to be planned with the Gridform tool to ensure the improvement of the accuracy is less than ±5%. The more accurate the tool the better planning of finite capital resources can be done and the larger impact that can be made. The case study microgrid projects were solely solar based. The framework has been built to enable any generation source. The deployment of the tool for use with generation sources would validate the capabilities of being generation source agnostic. Further optimization of the code to run on an offline tablet would be beneficial to allow practitioners on the ground the ability to plan with the villages what the final system would look like and cost, and would reduce the entire project timeline. The last improvement would be the creation of an end to end microgrid planning and analysis toolset either through APIs or brought into one platform by merging existing tools together such as HOMER and Gridlab D.

5.2 Microgrid Availability Analysis

In general, power systems and microgrid analyses will continue to evolve and improve over time. These efforts will help determine the risks and provide insight into the pathway(s) forward. As more information becomes available in much larger the ability to digest this without information overload will be critical. The visualization of results will be key. The microgrid availability analysis and code can be enhanced in a couple of areas. The precomputation of the power system using a general methodology of preconditioners and making the connection / network matrix more diagonally dominated will decrease the computation time of running the tool as larger systems are analyzed. This is the majority of the wait time. The main input is the one line diagram of the power systems. The creation of a front-end tool that can rapidly create a digital twin of the real system would be an enormous improvement to the entire field. This is the major pain point for analysis work is how to get information on the smaller scale power system.
5.3 Microgrid Modeling and Control

As new models get developed and existing models get improved the adoption of new technologies in the power systems community will be achieved. The achievement of “plug and play” capabilities is one step closer with the use of a CHIL platform. This past work and future would will be continued on the EPHCC github repository and funding for this effort has received increased funding.

This CHIL space is a rich frontier of options for future work. As new power systems equipment gets manufacture development, testing, and validation will be needed. The HIL platforms have the computation capability to perform a wide array of protection system testing and evaluation, distributed generation prime mover controller testing, integration and testing of distribution control systems, behavior testing and studies of DER controls, detailed power systems analysis, communications testing and integration, and implementation and evaluation of smart grid concepts. On aspect of future work is the development of the IEEE P2030.7 and P2030.8 microgrid standards that has and will continue to use MIT LL CHIL testbed as these standards get developed and voted on. There is a large number of existing power equipment that needs to be modeled and validated to the physical equipment, and to date less than a dozen pieces of existing power equipment has a digital twin created. The last focus, though definitely not the least is the use of the CHIL platform for cyber security development, testing, and performance validation.

As microgrids are developed additional one line diagrams and monitoring of test feeders will become more important to test out new ideas. This work found and created a digital twin of a real system that can be used by the power systems community. Future work can include making more power systems networks with monitoring capability more available.
Chapter 6: Conclusions

This work demonstrated an improved approach to planning microgrids via satellite imagery, the contribution of an anonymized real world test feeder to the power systems community, transition of that geospatial information to a digital twin for an analysis of microgrid availability, and the process of developing a controller hardware in the loop platform to integrate physical equipment controllers from manufacturers and the development, testing, and validation of models by applying a general framework.

The models in the Matlab SimPower Systems library have been expanded with better developed models of common power system equipment for microgrid controller testing, and reproduced an accurate digital twin model of a feeder level microgrid. Two symposiums in November 2015 and February 2017 were organized to demonstrate the CHIL testbed where multiple industry vendors tested their microgrid controllers. The development, testing, and validation of power system equipment can be an expensive and time consuming process. A CHIL platform reduces the risk and time while increasing the test coverage. This work demonstrated a subset of the capabilities in reducing the risk of new technology from new equipment manufacturers. The testbed was able to test microgrid controllers under a variety of scenarios, including islanding, short-circuit analysis, and cyber attacks. The focus is continuing on expanding the library of models and validating with physical equipment. This will result in another symposium with additional microgrid controller vendors and other integrated power equipment.
Appendix

A. Gridform Code
See Github Account: https://github.com/PowerSystemsHIL/EPHCC

B. Anonymized Power System
This is the power system for a new IEEE reference. This is the smaller feeder called Sheriff and the larger one is Banshee. Both have been posted to the Github Repository.

C. Framework Template for Power System Digital Twin Characterization
See Github Account: https://github.com/PowerSystemsHIL/EPHCC

D. Microgrid Availability Analysis Code
See Github Account: https://github.com/PowerSystemsHIL/EPHCC

E. Models
Diesel Generators.mdl
See Github Account: https://github.com/PowerSystemsHIL/EPHCC
Inverter Controllers.mdl
See Github Account: https://github.com/PowerSystemsHIL/EPHCC
Bibliography


[6] Electric Railway Review, Volume 5, Published 1895 Original from the University of California, Digitized Jan 13, 2014


