Energy Research and Development Division
FINAL PROJECT REPORT

CERTS MICROGRID DEMONSTRATION WITH LARGE-SCALE ENERGY STORAGE AND RENEWABLES AT SANTA RITA JAIL

Prepared for: U.S. Department of Energy

Prepared by: Chevron Energy Solutions Company
A Division of Chevron U.S.A. Inc.

MAY 2014
DE-FC26-08NT02872

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Cooperative Agreement Award Number:
DE-FC26-08NT02872

Prepared for:
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PREFACE

This is the final report for the CERTS Microgrid Demonstration with Large-Scale Energy Storage and Renewables at Santa Rita Jail project, Cooperative Agreement Number DE-FC26-08NT02872, conducted by Chevron Energy Solutions Company, a Division of Chevron U.S.A. Inc. The information from this project contributes to Energy Research and Development Division's CFDA Number 81.122 Electricity Delivery and Energy Reliability, Research, Development and Analysis Program.

ABSTRACT

The purpose of this report is to review the scope, methods, and major findings from the CERTS Microgrid Demonstration with Large-Scale Energy Storage and Renewables at Santa Rita Jail project. The main scope of this project was to demonstrate the commercial viability of a CERTS microgrid. A microgrid was achieved at the facility by integrating in the ability to island from the utility and resynchronizing back to it automatically. A large-scale energy storage system is used to support the facility during islanding events. During normal operation, when the facility is connected to the grid, the energy storage system has the added benefit of saving the facility money by buying and storing energy at off-peak hours and using the energy during peak hours. As an added benefit, the energy storage system serves to help relieve the strain on the utility's distribution feeder. The Santa Rita Jail Microgrid serves as a demonstration that a CERTS microgrid is possible.

Keywords: microgrid, energy storage, renewable, smart grid, distributed generation, distributed resources, islanding, CERTS

Please use the following citation for this report:

Alegria, Eduardo, Anthony Ma, Osama Idrees. (Chevron Energy Solutions). 2014. ***CERTS Microgrid Demonstration with Large-Scale Energy Storage and Renewables at Santa Rita Jail.*** U.S. Department of Energy. Publication number: DE-FC26-08NT02872

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LIST OF ABBREVIATIONS

A	Ampere
AC	Alternating Current
AES	Advanced Energy Storage
BIL	Basic Insulation Level
BMS	Battery Management System
CAISO	California Independent System Operator
CEC	California Energy Commission
CERTS	Consortium for Electrical Reliability Technology Solutions
CES	Chevron Energy Solutions
CIGRE	International Council on Large Electric Systems
DC	Direct Current
DER	Distributed Energy Resources
DER-CAM	Distributed Energy Resources Customer Adoption Model
DERMS	Distributed Energy Resources Management System
DOE	Department of Energy
EMTP	Electromagnetic Transient Program
f	Frequency
HMI	Human Machine Interface
Hp	Horsepower
Hz	Hertz
IEEE	Institute of Electrical and Electronics Engineers
kA	Kilo-Ampere
kV	Kilovolt
kVA	Kilovolt-Ampere
kVAR	Kilovolt-Ampere Reactive
kW	Kilowatt

kWH .... **Kilowatt Hour**

LBNL .... **Lawrence Berkeley National Laboratory**

LEED .... **Leadership in Energy and Environmental Design**

$LiFePO_4$ .... **Lithium Iron Phosphate**

ms .... **Millisecond**

MVA .... **Megavolt-Ampere**

MW .... **Megawatt**

MWH .... **Megawatt-Hour**

NAESCO .... **National Association of Energy Service Companies**

NREL .... **National Renewable Energy Laboratory**

ORNL .... **Oak Ridge National Laboratory**

PCC .... **Point of Common Coupling**

PCS .... **Power Conversion System**

PG&E .... **Pacific Gas & Electric**

PNNL .... **Pacific Northwest National Laboratory**

PPM .... **Partial-Peak Morning**

PSLF .... **Power System Loadflow**

PV .... **Photovoltaic**

R&D .... **Research & Development**

RMS .... **Root Mean Square**

SCADA .... **Supervisory Control and Data Acquisition**

SDS .... **Static Disconnect Switch**

sec .... **Second**

SNL .... **Sandia National Laboratory**

SOC .... **State of Charge**

SRJ .... **Santa Rita Jail**

TOU .... **Time-of-Use**

UW .... **University of Wisconsin**

V .... **Voltage**

WARF .... **Wisconsin Alumni Research Foundation**

WEMPEC .... **Wisconsin Electric Machine and Power Electronic Center**

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EXECUTIVE SUMMARY

This report documents the technical and scientific findings from the Consortium for Electrical Reliability Technology Solutions (CERTS) Microgrid Demonstration with Large-Scale Energy Storage and Renewables at Santa Rita Jail project. This project was a demonstration of a CERTS Microgrid. What distinguishes a CERTS Microgrid is its presentation to the rest of the distribution grid as a self-controlled entity; a CERTS Microgrid is indistinguishable to the utility from other facilities that do not include distributed energy resources. A significant benefit of a CERTS Microgrid is that it can meet its functional goals without the use of extensive custom engineering. A CERTS Microgrid is intended to offer its functionalities at lower costs than traditional approaches by eliminating the need for costly, high-speed control systems and by incorporating off-the-shelf components rather than custom made, one-off products. Microgrids without CERTS capabilities often have to invest significant costs into complex control systems and custom hardware in order to achieve the same performance as a CERTS microgrid. Since this CERTS microgrid project was the first of its type and scale, some of the major components were in fact custom designed to meet specific site and Utility requirements; however, the project proved that commercial CERTS Microgrids can be equipment agnostic just by following the CERTS protocol. The site of Santa Rita Jail (Figure 1) was selected due to its preexisting renewables, susceptibility to utility power quality events, and potential for utility rate arbitration. Led by Chevron Energy Solutions (CES), a team of researchers and contractors worked together to design, construct, and commission the microgrid. This project delivers a CERTS microgrid that is able to island from the utility and resynchronize back to the grid automatically. To achieve this capability, a very fast static disconnect switch (SDS) was installed at the facility's point of common coupling. The facility is able to maintain power in island mode by dispatching power from its 2-MW, 4-MWh energy storage system. During normal operation, i.e., not islanded from the grid, the energy storage system is programmed to charge and store during lower utility rate hours and to discharge its energy during high utility rate hours. By doing so, the facility is able to save money on utility charges. The benefit to the utility is that the loading on its distribution feeder is reduced during peak operation time which serves to extend the operational life of the equipment. The Santa Rita Jail Microgrid project serves as proof to the feasibility, operability, and benefits of a CERTS Microgrid in a real-world application.

Figure 1: Alameda County Santa Rita Jail

Photo Credit: Chevron Energy Solutions

CHAPTER 1:
Project Background

1.1 SRJ Existing

Rapid energy demand growth in California is outstripping the capacity of the state's energy infrastructure. Population growth is a major factor driving the energy demand growth. A second major factor is the attendant commercial expansion that accompanies that population growth. California's current population of 35 million is expected to grow by 71% to over 60 million by the year 2050. [1] This increase of over 25 million Californians will tax the current energy infrastructure to the breaking point. The problem is not a distant 43 years in the future − a 2005 report indicates that during the next ten years the western region of North America will fall short in bringing new energy capacity on line by approximately 4,000 megawatts. [2] As the energy demand in California increases, restrictions on coal-fired and nuclear plants, as well as environmental concerns surrounding energy exploration, will further constrain the ability to bring new power on line.

Santa Rita Jail is located in Dublin, California, the fastest growing jurisdiction in Alameda County. With a 5.4% population growth rate [3], Dublin's population is growing four times faster than California as a whole. The San Ramon feeder that serves the Santa Rita Jail has had an increasing amount of reliability issues. [4] Table 1 summarizes power interruptions between the years 2002–2006.

Table 1: Santa Rita Jail Distribution Feeder Five-Year Outage History

Date	Minutes Out of Service
12/16/2002	287
10/16/2004	80
10/20/2005	3
12/13/2005	Momentary
01/26/2006	56
01/29/2006	Momentary
03/21/2006	Momentary
03/26/2006	26
09/08/2006	6
10/09/2006	Momentary
Five-Year Total	458

1.1.1 Insufficient Customer Power Quality and Reliability

Power reliability is extremely important to operations at Santa Rita Jail (SRJ). SRJ's ultimate goal is to deliver uninterrupted power for all loads. During a power outage, the jail experiences approximately 15 seconds of complete downtime before the two 1.2-MW diesel generators are brought on line. The generators initially supply power to only the most critical life/safety systems (A Loads) at the facility. After both diesel generators are in service and in stable operation, some non-critical systems (B Loads) are systematically brought on line. The least critical loads (C Loads) remain out of service until Pacific Gas & Electric (PG&E) power is fully restored. In 2006, Santa Rita Jail experienced three sustained interruptions lasting a total of 88 minutes and three momentary interruptions. SRJ's longest outage occurred in 2002, lasting over five hours. [4] SRJ needed a new approach to achieve uninterrupted power supply for all of its loads.

At Santa Rita Jail, power reliability is essential for the Alameda County Sheriff's Office to provide a safe, secure, and humane environment for inmates and staff. According to Santa Rita Jail Captain Bert Wilkinson:

> *"With about 4,000 inmates housed in eighteen housing units, it is easy to understand that any interruption in the electricity potentially puts our deputies in harm's way. . . When the lights go out because of a power outage, those few seconds it takes for our emergency generators to bring the lights back on seems like an eternity to a deputy who is in the process of moving inmates within the jail."*

In addition, when an outage occurs, the inside air temperature at the jail can rise quickly because the jail's central chilled water system is unable to run on generator power. This poses an additional security risk.

Santa Rita Jail is recognized as one of the most technologically innovative jails in the world. As such, the numerous electronic systems that the jail relies upon are susceptible to failure if the electrical distribution system experiences power quality issues. The CERTS microgrid would resolve power quality problems, such as voltage spikes and sags.

1.1.2 Under-Utilization of Distributed Energy Resources

Alameda County's Santa Rita Jail is an award-winning leader in the installation of clean, distributed energy resources (DER). However, Santa Rita Jail's 1.2-MW photovoltaic (PV) system and 1-MW ultra-clean fuel cell (Figure 2) have not consistently reduced peak load nor are available as back-up power sources due to interconnection requirements.

Due to PG&E interconnection requirements, the PV and fuel cell systems are designed to discontinue generation when power is disrupted. Also, the fuel cell will disconnect if it detects voltage deviations (spikes or sags) from the grid. When this occurs, the fuel cell requires eighteen hours to resume full power. During this time, SRJ's peak load on the distribution feeder can spike.

Figure 2: 1-MW Fuel Cell at Santa Rita Jail

Photo Credit: Chevron Energy Solutions

The PV system at the jail is an intermittent power source that cannot consistently reduce peak load. Weather changes can dramatically impact the amount of peak power supplied on any given day. SRJ was in the forefront of PV installation when it installed the nation's largest rooftop solar project in 2002 (Figure 3). However, the PV system's inverters do not meet current interconnection standards, which precludes SRJ from net metering programs. SRJ's solar electricity generation sometimes exceeds local demand resulting in wasted over-generation. Despite significant investment in distributed resources, SRJ cannot consistently reduce peak load, limiting benefits to the end user and the distribution system.

Figure 3: Rooftop Solar Photovoltaic Array at Santa Rita Jail

Photo Credit: Alameda County

1.1.3 Diesel Generator Air Quality Impact

As Alameda County's largest energy-consuming facility, Santa Rita Jail is under substantial pressure to minimize its emission of pollutants, especially given its location in one of the strictest air quality management districts. SRJ's two large 1.2-MW diesel generators (Figure 4) can emit significant amounts of toxic air contaminants, criteria pollutants, and greenhouse gases. Furthermore, unlike many jails, SRJ is located near a heavily populated area, not to mention the 4,000 inmates and jail staff that could be exposed to pollutants during power outages. SRJ has had to accept these environmental risks because of its critical need for back-up power, which until now could only be supplied by polluting diesel generators.

Figure 4: 1.2-MW Diesel Generators at Santa Rita Jail

Photo Credit: Chevron Energy Solutions

1.1.4 Limitations of Centralized Command and Control of Distributed Energy Resources

There are technical difficulties related to the control of a significant number of distributed energy resources. The current focus on development of fast sensors and complex control from a central point provides a potential for failure. The fundamental problem with a complex control system is that failure of a control component or a software error will bring down the entire system. The SRJ Microgrid project's approach avoids this complexity by depending on the autonomous response of each DER unit to events using only local information.

1.1.5 The Solution

The overarching goals of the project were to significantly reduce peak load and improve power reliability at Santa Rita Jail (see Chapter 3 for the complete list of project objectives and results).

The project bolsters Santa Rita Jail's existing distributed energy resources with a CERTS microgrid combined with large-scale energy storage in order to significantly reduce peak load and improve customer power reliability with the additional benefit of reducing diesel generator emissions. Three key enabling technologies comprised the demonstration project:

1. CERTS microgrid
2. Advanced large-scale energy storage
3. Advanced communication and control systems

These technologies will be discussed further in Section 2.2.1.

1.2 Project Development

Chevron Energy Solutions assembled a complete and robust team of partners and advisors, all of whom are experts in their respective fields. The inclusion of multiple stakeholders throughout the process was critical for promoting long-term commercial success.

1.2.1 Team and Partners

1.2.1.1 Board of Advisors

The proposed project was supported by the foremost experts in CERTS technology which were complemented by experienced, well-connected leaders in the distributed energy profession.

Eduardo Alegria, Senior Power Systems Engineer, Chevron Energy Solutions

Eduardo Alegria applies his more than 20 years of power systems research, applications and field experience to find the most innovative, efficient power conditioning solutions. Before joining Chevron Energy Solutions, Mr. Alegria worked at Pacific Gas and Electric Company (PG&E) as Manager of the Premium Power Consulting Group. He was responsible for the development of power conditioning products, services and equipment. While working for PG&E, Mr. Alegria developed the first commercial application of a 25-kV class static transfer switch.

Joe Eto, Staff Scientist, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory

Joe Eto's principal responsibility is management of the Consortium for Electric Reliability Technology Solutions (CERTS). Mr. Eto has authored over 150 publications on electricity policy, electricity reliability, demand response, distributed energy resources, utility integrated resource planning, demand-side management, and building energy-efficiency technologies and markets.

Robert Lasseter, CERTS Technical Lead, University of Wisconsin Emeritus Professor

Professor Lasseter is the technical lead on a multi-million dollar CERTS/CEC project focused on microgrids. He is a member of CIGRE TF38.01.10 "Modeling New Forms of Generation and Storage," and chairman of the Institute of Electrical and Electronics Engineers (IEEE) Working

Group on modeling and analysis of distributed resources. In the last five years he has given over eighty seminars and lectures on distributed generation and microgrids. Professor Lasseter provided technical oversight to this project.

Janice Lin, Managing Partner, Strategen Consulting

Prior to founding Strategen, Ms. Lin held several senior management positions with PowerLight Corporation, a leading designer and installer of large-scale grid-connected solar electric systems and energy efficiency services. These roles included Vice President of Product Strategy, Vice President of Business Development, and Director of Business Development. Ms. Lin's extensive contacts throughout the energy industry were instrumental in bringing the partner team together and helped secure future support.

1.2.1.2 Project Partners

Listed below are the project partners:

- Chevron Energy Solutions (CES)
- Alameda County
- California Independent System Operator (CAISO)
- Pacific Gas and Electric Company (PG&E)
- National Renewable Energy Laboratory (NREL)
- The University of Wisconsin (UW)
- Consortium for Electric Reliability Technology Solutions (CERTS)
- Lawrence Berkeley National Laboratory (LBNL)

The project partner roles are listed in Table 2.

Table 2: Project Partner Roles

Partner	Role
Chevron Energy Solutions	Team Lead and General Contractor
Alameda County (Santa Rita Jail)	End Customer and Microgrid Owner
Pacific Gas & Electric	LSE Interconnection & Communication
California Independent System Operator	System Operator: Grid Interoperability Testing & Market Design
University of Wisconsin, The Wisconsin Alumni Research Foundation	CERTS License Provider and Technical Oversight
National Renewable Energy Laboratory	Measurement & Verification
Lawrence Berkeley National Lab	Storage Scheduling Optimization

Chevron Energy Solutions: Team Lead and General Contractor

Role

Chevron Energy Solutions (CES) had the overall responsibility for designing and installing a complete integrated microgrid/energy storage system. CES was the central focus for communication and coordination of all the other team members. CES commissioned the complete system after each of the individual components were commissioned and ready for service. CES monitored and reported on system performance. All team members were subcontractors to CES, except for Alameda County, which contracted with CES to engineer, procure and construct the microgrid system.

Capabilities

Chevron Energy Solutions has 35 years of experience in the energy services industry providing clients a variety of services from energy audits to bill aggregation and payment. CES employs over 300 energy professionals including over 100 operations personnel and over 80 degreed engineers from a multitude of disciplines.

In addition to the degreed and experienced staff, CES is fully accredited as an Energy Services Provider by the National Association of Energy Service Companies (NAESCO). NAESCO accreditation recognizes a company's technical and managerial competence. Accreditation is granted after careful review by an independent panel of industry experts.

CES is a member in good standing and is participating in the Leadership in Energy and Environmental Design (LEED™) for existing buildings and new construction initiatives. CES has a number of LEED-accredited professionals.

The CES team of energy professionals has the experience, technical skills, resources and determination to be leaders in the emerging microgrid and advanced energy storage markets.

Alameda County: End Customer and Microgrid Owner

Role

Alameda County is the owner of the Microgrid project at its Santa Rita Jail and contracted with CES for the design and installation of the microgrid equipment. Energy Program Manager Matt Muniz, P.E., was the project manager, overseeing all aspects of the project for the County and was the County's main point of contact. Alameda County provided design review and approval and coordinated construction and commissioning activities with the operations at the jail facility.

Capabilities

Santa Rita Jail, a one-million-square-foot facility housing over 4,000 inmates, is the fifth largest county detention facility in the nation and Alameda County's largest energy-consuming facility. Alameda County has a long history of successfully installing cutting-edge renewable and ultra-clean onsite generation at its facilities. Currently the County generates 25% of its electricity from 3.1 MW of onsite solar power systems and a 1-MW fuel cell cogeneration plant. These systems include one of the largest rooftop photovoltaic systems in the U.S., two large solar tracking carports, and California's first megawatt-class fuel cell cogeneration system. These efforts have been recognized as a model for other governmental agencies and illustrate Alameda County's continuing national leadership role in sustainable local government operations.

Pacific Gas and Electric Company (PG&E): Load-Serving Entity Interconnection and Communication

Role

Pacific Gas and Electric Company specified the requirements for the interconnection of the Santa Rita Jail microgrid system to their distribution system. PG&E researched and provided an advanced SCADA system to improve communications and controls and to monitor power quality. Additionally PG&E provided the communication system to allow the battery to be dispatched when required by distribution systems operations.

Capabilities

Pacific Gas and Electric Company, incorporated in California in 1905, is one of the largest combination natural gas and electric utilities in the United States. Based in San Francisco, the company is a subsidiary of PG&E Corporation. There are approximately 20,000 employees who carry out PG&E's primary business – the transmission and delivery of energy. The company provides natural gas and electric service to approximately 15 million people throughout a 70,000-square-mile service area in northern and central California.

PG&E is routinely recognized for its environmental leadership. PG&E has connected more than 15,000 customer-owned solar energy systems to California's electric grid, more than any other utility in the country. PG&E also spearheaded nearly $1 billion in enhanced energy efficiency programs for its customers from 2006 to 2008 – the largest effort of its kind by a U.S. utility company.

California Independent System Operator (CAISO): Grid Interoperability Testing and Market Design

Role

California ISO worked with the project team to demonstrate the value of energy storage systems and interoperability of microgrids with the system grid. CAISO tested the communication linkage between their facilities and the test facility.

Capabilities

CAISO's support of this project greatly improved the ease of interconnection and enabled market acceptance of microgrids and advanced energy storage. CAISO is a not-for-profit public benefit corporation charged with managing the flow of electricity along California's open-market wholesale power grid. CAISO's mission is to safeguard the reliable delivery of electricity and ensure equal access to 25,000 circuit miles of "electron highway." As the impartial operator of the wholesale power grid in the state, CAISO conducts a small portion of the bulk power markets. These markets are used to allocate space on the transmission lines, maintain operating reserves, and match supply with demand in real time.

University of Wisconsin, The Wisconsin Alumni Research Foundation (WARF): CERTS License and Technical Oversight Provider

Role

WARF provided the CERTS license to the project. The University of Wisconsin (UW) acted as the microgrid technical oversight. Emeritus Professor Bob Lasseter and his associates reviewed the project design and specifications to ensure that the installed system met the project objectives. Professor Lasseter's team modeled the microgrid battery system electrical and controls dynamics and advised the design team of the modeling results.

The Consortium for Electric Reliability Technology Solutions (CERTS) was formed in 1999 to research, develop, and disseminate electric reliability technology solutions in order to protect and enhance the reliability of the U.S. electric power system under the emerging competitive electricity market structure. The founding members include four DOE National Labs (Lawrence Berkeley National Laboratory (LBNL), Sandia National Laboratory (SNL), Oak Ridge National Laboratory (ORNL), and Pacific Northwest National Laboratory (PNNL); National Science Foundation's Power Systems Engineering Research Center; and the Electric Power Group. Currently, CERTS is conducting public interest research for the DOE Office of Electricity Delivery and Energy Reliability and the California Energy Commission (CEC) Public Interest Energy Research program.

Dr. Lasseter and colleagues at the University of Wisconsin provided implementation assistance for each CERTS component. This included detailed functional specifications and assistance in understanding and debugging the control algorithm. UW assisted in the development of factory tests for each CERTS component and, where possible, provided EMTP simulations illustrating the expected response. The data from the factor tests included time traces of the voltage, current, frequency, real power and the reactive power during an event.

UW also participated in all design review activities and provided necessary support on the microgrid system design and assisted in the development of component and system commissioning tests for each CERTS component and their interaction within the system. UW provided EMTP simulations where possible to illustrate the expected response during these tests. UW also assisted in the commissioning and functional tests for the system as a whole.

Capabilities

The University of Wisconsin has one of the world's top power electronics and distributed energy centers. Wisconsin Electric Machine and Power Electronic Center (WEMPEC) has over 7,800 square feet of research and teaching laboratory space devoted to electric machines, power electronics, electric drive systems, power quality, motion control and distributed resources.

WEMPEC Microgrid Emulator is used to design operational and control concepts for multiple distributed resources. Inverter-based microsources such as a Capstone microturbine, Tecogen's inverter-based ICE-driven generator, and inverter-based renewables and fuel cells are emulated using 50-hp Allen Bradley inverters with the prime mover plus DC storage emulated using a 700-Vdc power supply. The inverter-based sources are limited to 15 kVA. WEMPEC currently has one non-inverter-based source. This is a 12.5-kVA diesel-generator set with a wound-field synchronous machine with modifiable controls.

The microsources generate power at the voltage level of 480V appropriately lowered to the network voltage by a separate transformer. In series to the microsource there is an inductance to allow for power transfers. There are two load centers located near the two microsources and another load electrically installed between the two units: this allows testing of the power sharing during operation in island mode.

The three-phase passive loads are connected in a Y-configuration, while the cables consisting of four conductors, three phase lines and a neutral line, run in parallel from one bus to the next, representing the feeder. Microsources are connected to the local feeder with a transformer in series to an inductance. The connection is at delta on the source side and at wye on the feeder side with the center star connected to the neutral wire of the feeder cable. The voltage level of the feeder is 208V, while the source operates with voltages of 480V. This system has been used to design and test the CERTS microgrid control and operational concepts.

National Renewable Energy Laboratory (NREL): Measurement & Verification

Role

NREL provided system evaluation and data analysis. NREL worked with team partners to evaluate the integration of renewable and distributed energy systems into the electrical distribution system. This included the evaluation of distributed resource integration design in conformance to appropriate interconnection and interoperability standards, determination of operational performance requirements, evaluation of the benefits of the system including expected peak load reduction and the ability to improve reliability, and conduct economic evaluations of the system. NREL also worked with team partners to evaluate and conduct analysis on the integration of renewable and distributed energy systems into the electrical distribution system. This included comparing the measured system performance data to models and simulation as well as helping to independently verify system operation and performance. NREL delivered annual reports on NREL activities including system evaluation and system performance verification.

Capabilities

NREL is the nation's primary laboratory for renewable energy and energy efficiency research & development (R&D). NREL's broad areas of expertise include:

- Renewable electricity – solar, wind, biomass, geothermal
- Renewable fuels – biomass, hydrogen
- Integrated energy system engineering and testing – buildings, electric systems and transportation infrastructures
- Strategic development and analysis – economic, financial, and market analysis, planning and portfolio prioritization

NREL provided system evaluation and data analysis to the project, and provided expertise in distributed PV resources, energy storage, and distribution system configurations, communications, and control. Electric infrastructure systems R&D at NREL is focused on distributed energy testing and certification, interconnection standards and codes, interconnection and control technologies, energy management and grid support applications, and distributed energy regulatory and institutional issues. These research areas support NREL's Distributed Energy and Electric Reliability Program. NREL's energy management and grid support activities investigate technologies and methods that enable distributed energy resources to make full-value contributions to the electric grid.

Lawrence Berkeley National Laboratory (LBNL): Scheduling Optimization

Role

LBNL analyzed the microgrid at the Santa Rita Jail facility and determined the optimal economic operation of the various distributed generation resources. The Lab built a Distributed Energy Resources Customer Adoption Model (DER-CAM) representation of the jail's multiple generation assets (PV, fuel cell, and backup generators) and efficiency options (alternative tariffs, optimal scheduling, load shedding, etc.), and established an optimal operating schedule for all resources including the battery flow.

Capabilities

LBNL has completed a considerable body of work analyzing on-site generation potential of commercial buildings, especially in hot climates where absorption cooling is the most economically attractive heat sink. This work has led to the development of the DER-CAM, which finds optimal combinations of equipment to install and optimal operating schedules for them, as well as multiple studies of actual systems. DER-CAM is copyrighted to the Lab and is licensed to several other research institutions. Under existing DOE contracts, development of capabilities relevant to this project are ongoing, particularly related to optimal storage operation and valuation of the incremental reliability and power quality capabilities that the DER-CAM provides. No other comparable capabilities are known to these researchers.

1.2.2 Funding Sources

U.S. Department of Energy funding for the *CERTS Microgrid Demonstration with Large-Scale Energy Storage and Renewables at Santa Rita Jail* was provided under Cooperative Agreement Number DE-FC26-08NT02872.

CHAPTER 2: Project Description

2.1 Project Scope

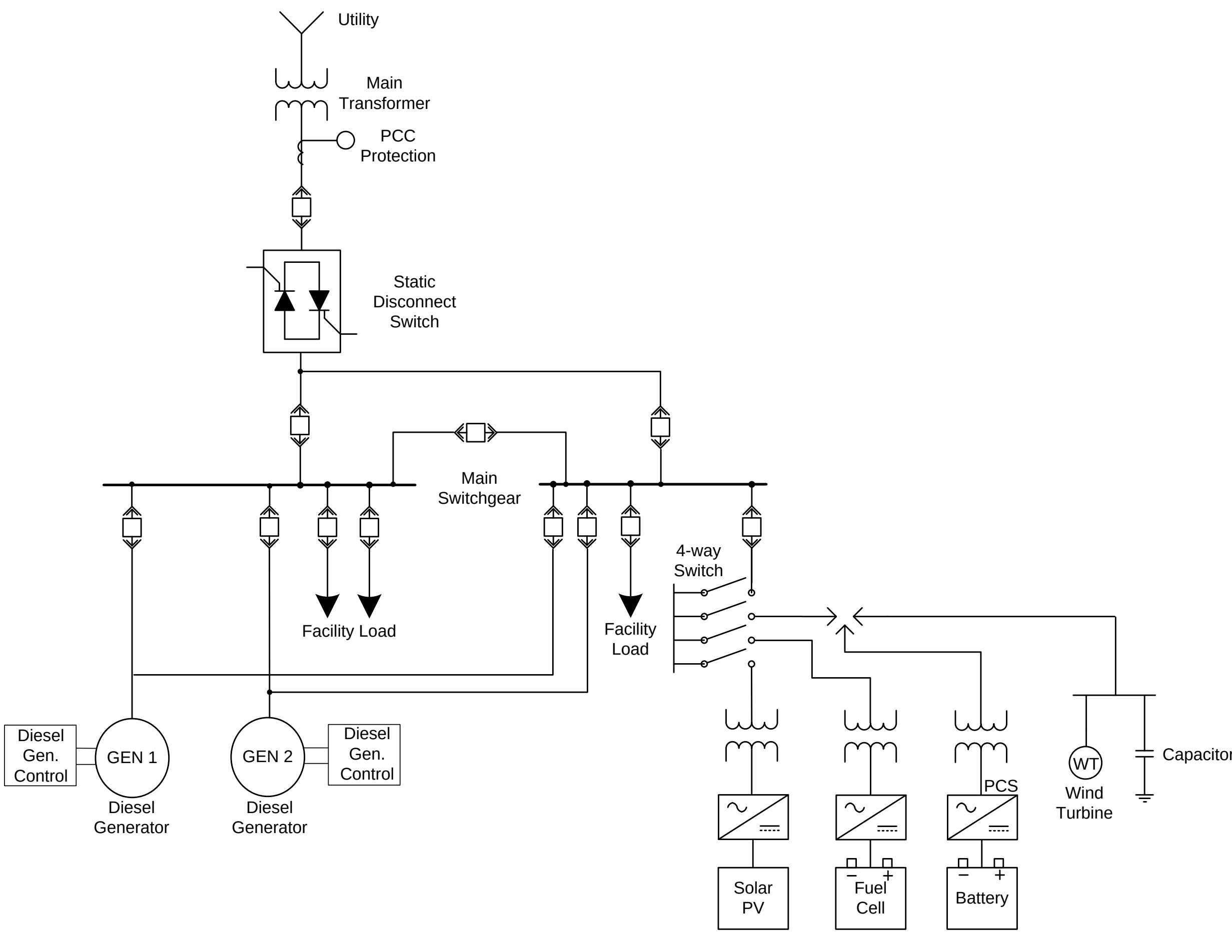
Prior to the Microgrid project, the Santa Rita Jail facility was susceptible to momentary utility outages and power quality events. Maintaining power free of momentary or sustained outages is critical to the safety of the officers, staff and inmates. To prevent sustained outages, diesel generators were available to power essential facility loads. However, the diesel generators relied on a load-shed system and required approximately 15 seconds to start, during which the facility had no power.

Additionally, the solar photovoltaic and fuel cell systems were unable to operate in parallel with the diesel generators. This was due to a couple of reasons. One, it is challenging for the system to maintain proper microgrid system voltage and frequency within operational limits during transitions to the back-up diesel generators. Secondly, the diesel generator frequency itself is not as stable as the grid and may trigger anti-islanding functions on PV or fuel cell inverters to trip the equipment offline. This is a disadvantage from an economic and environmental perspective because the clean, renewable sources were not being utilized during island conditions. Once utility power was restored, the fuel cell would take approximately 18 hours to restart, resulting in increased demand and energy charges on the utility bill. The solar photovoltaic and fuel cell operations also were impacted by utility power quality events such as voltage sags [5] [6]. These impacts related to utility issues were resolved with incorporation of a fast static disconnect switch (SDS), which enabled autonomous operation and seamless islanding of the jail.

The jail's ability to autonomously island was key to providing the highest system reliability. Due to the practical limitations of matching the existing generation and load for a successful island transition, advanced energy storage (battery) was utilized to stabilize system voltage and frequency during transient conditions. Using CERTS Microgrid protocol helped simplify the integration of the battery and SDS with existing on-site resources. The "plug-and-play" nature of the CERTS protocol gives CERTS-based sources (diesel generators and battery) the ability to interconnect with each other without the need for a customized supervisory generator control system.

In addition to the battery providing system reliability and stability, it is also used to optimize on-site generation to decrease the total cost of energy purchased from the utility. The current utility tariff schedule has time-of-use rates under which energy consumption and maximum power demand vary based on time of day and season. The battery stores energy purchased during less-expensive off-peak periods to be utilized during peak periods. The SRJ Microgrid single-line diagram is shown in Figure 5.

Figure 5: Santa Rita Jail Microgrid Single Line Diagram



Source: Chevron Energy Solutions

2.2 Project Implementation

2.2.1 Design

One of the objectives of the CERTS Microgrid concept was to reduce microgrid system cost and increase reliability. This includes *plug-and-play* functionality without communications. Plug-and-play concepts reduce engineering cost and errors since little site modification is required for different applications. Each CERTS device regulates voltage and frequency both grid connected and while islanded. These key concepts have been demonstrated at the American Electrical Power Microgrid Test Facility. This includes transient events such as seamless separation and automatic re-synchronizing with the grid, Class I level power quality during utility faults, large unbalanced loading, and stable operation during major events. [7] The CERTS concept has three critical components: the static disconnect switch, the microsources, and loads. The static disconnect switch has the ability to island the microgrid autonomously for disturbances such as faults, IEEE 1547 events, or power quality events. Following islanding, the reconnection of the microgrid is achieved autonomously after the tripping event is no longer present. Resynchronizing to the utility uses the frequency difference created by the islanding event. [8]

Each CERTS-controlled source seamlessly balances the power on the islanded microgrid using a power vs. frequency droop controller. In this project the battery storage system and the backup diesel generators have the CERTS frequency and voltage control. The fuel cell and the photovoltaic inverters run in a power mode and do not track load, control voltage or frequency. For example, if the load increases while in island operation, the storage system will provide the extra power instantaneously and increase the operational frequency. At maximum output the frequency controls are designed to drop no more than 1%. If there is inadequate energy to meet the load, the frequency will drop below the normal operating range, signaling the non-critical loads to shed. The coordination between sources and loads is through frequency.

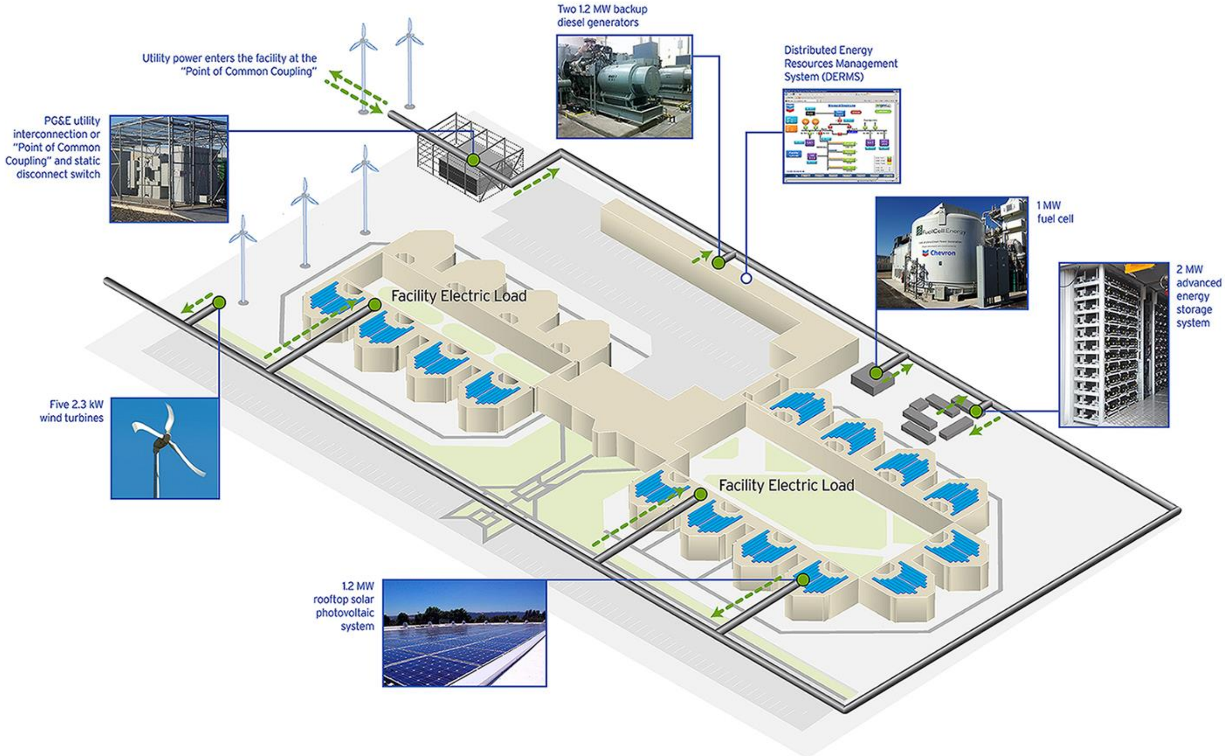
The storage inverters and the diesel generators not only control the voltage but they also ensure that there are no large circulating reactive currents between units. With small errors in voltage set points, the circulating current can exceed the ratings of the units. This situation requires a voltage vs. reactive power droop controller so that, as the reactive power, Q, generated by the unit becomes more capacitive, the local voltage set point is reduced. Conversely, as Q becomes more inductive, the voltage setpoint is increased. At Santa Rita Jail this droop is 5%. In addition to the system voltage stability demonstrated at the American Electric Power (AEP) microgrid test site, extensive analysis indicates that the microgrid's stability is independent of the number of CERTS devices in a microgrid. [9] Theoretically the system would remain stable with an infinite number of CERTS units.

CERTS Microgrid controls do not rely on a "master" controller or source. Each source is connected in a peer-to-peer fashion with a localized control scheme implemented for each component. This arrangement increases the reliability of the system in comparison to having a master-slave or centralized control scheme. In the case of master-slave controller architecture, the failure of the master controller could compromise the operation of the whole system. Santa Rita Jail uses a central communication system to dispatch storage set points, voltage and power as needed to control the state of charge. However, this communication network is not used for the dynamic operation of the Microgrid. This plug-and-play approach allows for expansion of the Microgrid to meet the requirements of the site without extensive re-engineering. Plug-and-play implies that a unit can be placed at any point on the electrical system without re-engineering the controls, thereby reducing the chance for engineering errors.

The key considerations for the Microgrid system design were meeting the criteria for operation under the CERTS protocol and integrating with the existing infrastructure.

Figure 6 provides an illustration of the Santa Rita Jail's Microgrid components.

Figure 6: Santa Rita Jail Microgrid Components



Source: Chevron Energy Solutions

2.2.1.1 Battery

The battery technology selected for this project was a 2-MW, 4-MWh Lithium Iron Phosphate ($LiFePO_4$) battery (Figure 7). This is a type of lithium ion battery that uses $LiFePO_4$ as a cathode material. Several battery technologies were compared during the design process. Some of the highly weighted selection criteria included round trip efficiency, cycle life, maximum temperature rating, safety, environmental considerations, and maintenance requirements. Compared with other lithium-ion battery chemistries, the $LiFePO_4$ battery offers improved safety because of the thermal and chemical stability exhibited by the technology. The tradeoff is a slightly lower energy density than other lithium ion chemistries. The specified AC-AC round trip efficiency was 85% while the actual measured AC-AC round trip efficiency is 88%.

The energy stored in the battery is used for either tariff-based rate arbitrage or power quality and reliability. When grid connected, the battery charges or discharges as dictated by the Distributed Energy Resource Management System (DERMS) in order to maximize the economic benefit of the battery. The rate arbitrage scheme is based on the utility tariff structure and not on real-time pricing. During a grid disturbance or outage, the energy in the battery is used to continuously supply high quality power to the on-site loads.

Figure 7: Container with 500 kW of Lithium-Iron Phosphate Batteries

Photo Credit: Chevron Energy Solutions

The battery was sized at 2 MW, 2.5 MVA to be able to serve the facility demand, which peaks at 2.8 MW, 2 MVARs in the summer afternoons. This would allow the facility to island from the utility grid when the fuel cell or part of the PV system are on line, but may require load shedding in the unlikely event that all PV inverters and the fuel cell are off line.

The 4-MWh storage capacity was sized such that on a typical summer day the battery, fuel cell and solar photovoltaics could serve all of the facility peak-period energy usage. 80% of storage capacity is used for rate arbitrage, reducing the facility peak load. The remaining 20% is reserved for power quality events when the system transitions from grid connected to island operation. This provides enough energy to maintain the system until the diesel generator starts, if required. The battery has an upper and lower state-of-charge limitation of 90% and 10% respectively during grid-connected operations to maintain the reserve for power quality. To ensure reliability during island operation, a new load and generation management system was installed to control the shedding and adding of load and generation sources (i.e., PV generation or fuel cell) in order to prevent the battery from reaching a full charge or discharge state and shutting down.

2.2.1.2 Power Conversion System

A CERTS-compliant power conversion system (PCS) was required to interface the battery with the Microgrid and utility source (Figure 8). The installed PCS is rated 2 MW, 2.5 MVA, consisting of four DC-to-DC converters that interface with each of the four 500-kW, 1-MWh battery enclosures. Each of the battery enclosures is independent and capable of operating if any or all of the other three containers are shut down. There are two DC-to-AC inverters that interface with two DC-to-DC converters, each through a common DC link bus. This system architecture makes the system highly flexible, allowing for proper maintainability and testing. The PCS was sized such that it could supply some, but not all of the facility's reactive power needs. This is discussed further in section 2.2.1.3 Capacitor Bank.

Figure 8: Power Conversion System at Santa Rita Jail

Photo Credit: Chevron Energy Solutions

When grid-connected, the DERMS dispatches charge or discharge signals to the PCS to provide the highest level of economic benefit to the jail. To change the rate of power charge or discharge, the PCS responds to "raise speed" or "lower speed" signals, similar to those used in frequency/load control of traditional generation units. The PCS frequency droop curve moves up or down, without changing its slope, thus changing the rate of power charge or discharge of the battery. Similarly the reactive power flow is controlled with the voltage droop curve.

During the transition from grid-connected to island, the PCS remains connected, operating as a voltage source, even if the voltage and/or frequency are outside normal operation limits. The transient recovery voltage period is typically within one cycle, but may last several cycles depending on the circumstances of the islanding process. During this time, the PCS is constrained only by its internal current and power limiting functions.

When the Microgrid is islanded, the CERTS algorithm programmed in the PCS determines the appropriate battery charge and discharge levels within the range established by the frequency and voltage droop curves of the PCS. [10]

During passive synchronization with the utility, the PCS is required to remain on line even with a wider Delta V and Delta F synchronization window than traditionally used.

2.2.1.3 Capacitor Bank

The jail has high reactive power demands due to large rotating loads. This large reactive demand coupled with the on-site renewable sources operating near unity power factor led to a low power factor at the utility point of common coupling. Reactive power compensation would be needed in order to avoid low power factor penalties on utility billing. More importantly, according to a dynamic analysis study, the Microgrid would not be able to island successfully without another reactive power source supplying the rotating equipment. An economic analysis revealed that a capacitor bank was the preferred alternative for supplying the reactive power needs compared to increasing the PCS MVA rating. A 900-kVAR capacitor bank was installed to provide the remaining reactive power to allow the Microgrid to island and to improve the power factor at the utility point of common coupling.

2.2.1.4 Static Disconnect Switch

A static disconnect switch (SDS) was installed between the utility and Microgrid to allow for very fast islanding and autonomous operation of the Microgrid (Figure 9). There are voltage and current transformers on the line and load sides of the SDS to constantly detect the voltage and frequency of both the utility and Microgrid systems. These measurements allow the system to island during power failures or power quality events exhibited by the utility. The SDS operates within a quarter cycle on the order of 4 to 10 milliseconds. Disconnection and islanding from the utility are fast enough that any utility events go undetected by the inverter sources in the Microgrid.

Figure 9: Santa Rita Jail Static Disconnect Switch at Utility Point of Common Coupling

Photo Credit: Chevron Energy Solutions

The SDS is rated 12.47kV, 60Hz, three-phase, with a Basic Insulation Level (BIL) of 95kV, for use on a 4-wire solidly grounded system. It has a continuous and load-interrupting rating of 300A and an overload rating of 375A (125%) for 120 seconds. The unit thyristor valves have the capability to withstand the surge current of 35 kA for one cycle and 8 kA Root Mean Square

(RMS) symmetrical for fifteen (15) cycles. It was designed to operate with N+2 redundancy on the thyristor valve devices. This allows the SDS to operate with two thyristor levels shorted out. The overall efficiency is 99% or greater.

The SDS contains islanding and synchronization functions compatible with CERTS protocols. This requires passive synchronization, without the need for external signals for islanding or synchronizing.

Islanding operations are triggered by overvoltage, undervoltage, overfrequency and underfrequency. There is also directional overcurrent, required by the utility, with current flowing towards the utility grid programmed in the external protective relay that trips the main 12-kV utility breaker. These functions are coordinated with revised overvoltage, undervoltage, overfrequency and underfrequency settings in the fuel cell inverters and PV inverters to ensure that all renewable generation stays on line following an islanding transient. The protective setting ranges and implemented values for islanding are listed in Table 3.

Table 3: Protection Settings for the Static Disconnect Switch

Protective Function	Device Setting Range	Implemented Value
Overvoltage	105% – 115%	110%, 10ms (Fast) 115%, 2ms (Instantaneous)
Undervoltage	95% – 50%	80%, 10ms (Fast) 50%, 3ms (Instantaneous)
Overfrequency	60.1 Hz – 63 Hz	60.5Hz, 0.5ms
Underfrequency	59.9 Hz – 57 Hz	59.5Hz, 0.5ms
Directional Overcurrent	0% – 500%	130%, 60 sec

Source: Chevron Energy Solutions

This SDS was installed in conjunction with bypass and isolation switchgear to allow for servicing of the unit and shutdown in case of any failures.

2.2.1.5 Diesel Generator Upgrade

Santa Rita Jail has two 1.2-MW backup diesel generators. These diesel generators would operate only when there was a utility power outage. As part of the Microgrid, the generators are now operated to charge the battery if the battery has a low state of charge when islanded or if the Microgrid fails. This significantly reduces the operation time of the diesel generators. The old speed and voltage controls of the diesel generators were isochronous, meaning they maintained a constant frequency and voltage over any real and reactive power output, within the generators' rated capacity. The controls were modified and upgraded to be CERTS compliant. CERTS compliant means allowing voltage and frequency droop operation, similar to the operation mode used when operating diesel generators synchronized with the utility grid. Since controllers to operate reciprocating engine-generators synchronized to the utility grid are readily available, off-the-shelf generator control equipment was used for the diesel generator control upgrades, avoiding the need for costly specially designed equipment. This is one of the advantages of using CERTS; it simplifies the integration of renewable or large-scale energy storage equipment with conventional generation.

The Santa Rita Jail backup diesel generators are not permitted by air quality regulations to operate when utility power is available. When the microgrid islands due to a utility outage and the diesel generators are called into operation, the generators synchronize with the microgrid and operate in voltage and frequency droop mode (CERTS mode). In this mode of operation, the kW output of the diesel generators is controlled by biasing the frequency droop curve, without changing its slope, until the desired kW output is achieved. Again, this is similar to the strategy used to control kW output of conventional generators when operating synchronized to the utility grid.

To minimize the operating hours of diesel generators during a sustained utility outage, the diesel generators are only called into operation when needed, i.e., when the battery state of charge reaches a minimum island operation set-point. In addition, when operating in parallel with the microgrid, the kW output of the diesel generators is set to operate close to its rated output, where the operation is most efficient. However, by operating below rated output, there is margin in the output for the diesel generators to share frequency and voltage control functions with the battery per their respective voltage and frequency droop curves. The generators transition back to isochronous control in the event the Microgrid is not operational or when the battery is out service. In this case, the system operates just like a traditional backup generation system – the utility power outage would cause a brief power outage in the facility, followed by isochronous operation of the backup diesel generators.

2.2.2 Construction

Construction of the SRJ Microgrid project was completed in phases. First, a suitable location within the secured correctional facility was chosen for installation of the energy storage and generation system. The equipment included four containers approximately 40 feet in length, each containing 500 kW of Lithium-Iron batteries weighing 24 metric tons; power conversion system; 3-MVA transformer, static disconnect switch, Vista 4-Way Switch; and multiple communication systems. Underground electrical infrastructure was installed along with reinforced concrete foundation pads for the placement of equipment. Directional boring for installation of underground electrical conduits from the site of the equipment to the Point of Common Coupling (PCC) was performed during construction. Directional boring reduced the impact of the construction to ongoing operation of the facility.

The battery containers along with all other equipment were installed and secured onto the foundation pads with heavy rigging equipment with 250-ton lifting capacity (Figure 10). After placing the equipment, all electrical conductors and communication wiring were installed. Communication testing commenced after all infrastructure and equipment were installed. Operation and communication testing then commenced confirming functionality of the Microgrid system.

Figure 10: Battery Container Being Lifted onto Foundation Pad

Photo Credit: Chevron Energy Solutions

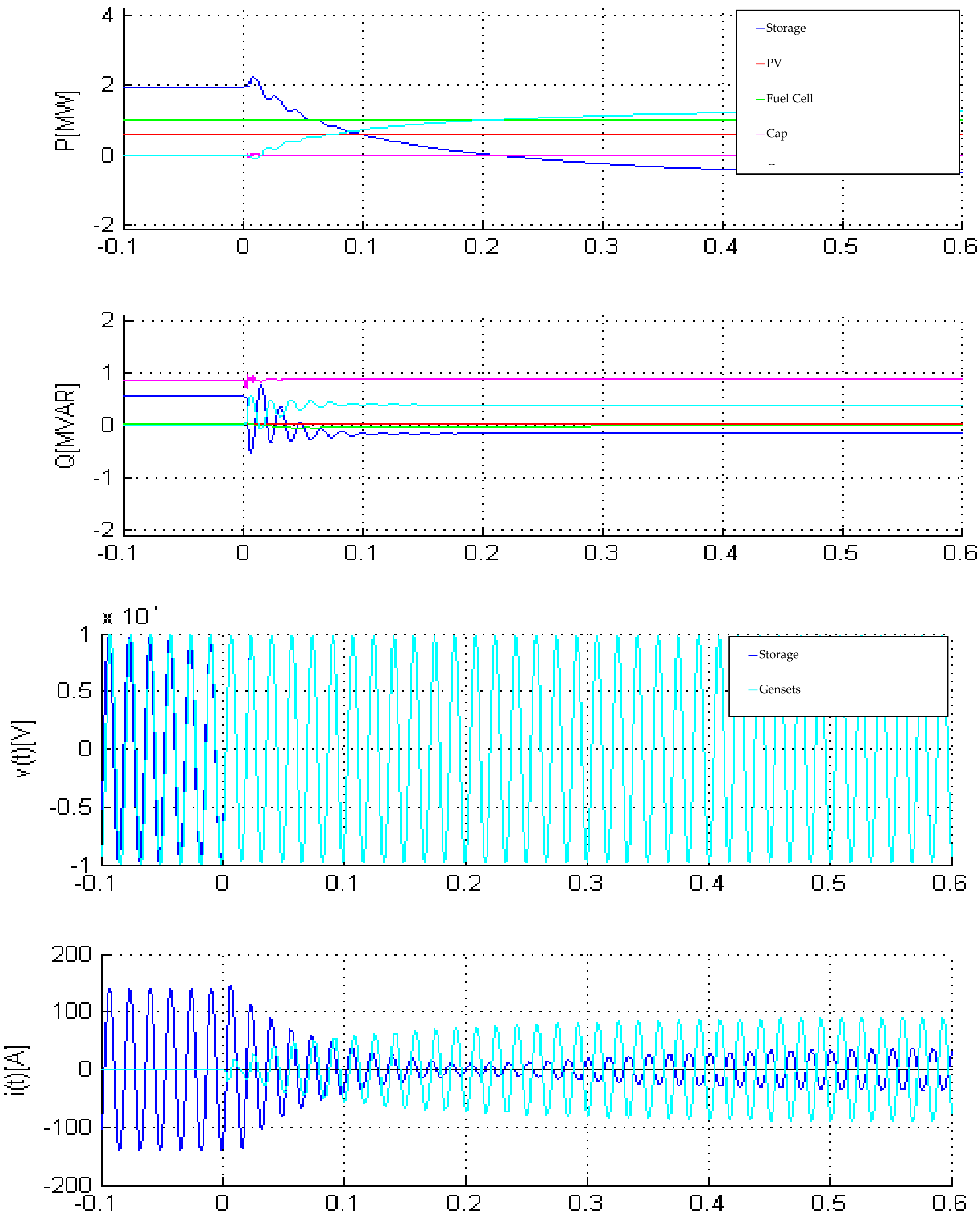
2.2.3 Commissioning

Commissioning of the microgrid system was completed in three phases. First, the system was studied through computer simulation in Power System Loadflow (PSLF) software. Next, the CERTS functionalities were tested on the PCS at the factory before shipment. Finally, the microgrid system was tested at the site with all the existing distributed energy resources.

2.2.3.1 Computer Simulations

Extensive system studies were performed to better understand the dynamic response of the microgrid. A PSLF model of the Santa Rita Jail system that included dynamic models of the battery system, diesel generators and rotating loads was completed. The PSLF model also included a thyristor-based switch at the PCC (modeled as a switching element able to respond in 10 milliseconds), and elements of the system that do not have a dynamic response to changes in voltage and frequency like the capacitor banks, fuel cell, PV system, cables, static loads, etc. See Figure 11. The PSLF model was verified with dynamic response tests performed during the PCS factory acceptance test and during commissioning tests at the Santa Rita Jail site.

Figure 11: Simulation of Starting Generators While Islanded (in Seconds)



Source: Chevron Energy Solutions

As an example, consider the transient when the two diesel generators are introduced to charge the storage system while in island operation. In this case the storage autonomously moves from maximum output of 2 MW to charging while increasing the island's frequency by approximately 1/4 Hz.

The top two plots in Figure 11 show the real and reactive power for the storage system, PV systems, fuel cell, capacitor bank, and the diesel generators. The lower two plots are phase-a current and voltage waveforms for the diesel generators and storage inverter. Before the diesel generators are introduced the storage is discharging at 2 MW. At time = zero seconds (t=0), the generators are connected. Once connected, the power transition between the battery and the generators takes approximately one second. The power oscillations seen here are a result of a non-zero load-angle during synchronization. The inertia of the diesel generator results in power fluctuations as the power accelerates and decelerates as a function of the position, resulting in a classical second-order response.

The synchronization process is evident from the relative blurring of the voltage waveform prior to t=0 and subsequent alignment of the voltage waveforms after synchronization. The power increase from the gensets and the subsequent reversal of power flow from the storage system is also evident in these figures. These voltage wave forms also demonstrate the robustness of the voltage controller during this event.

2.2.3.2 PCS Factory Acceptance Test

To ensure successful commissioning at the site, a complete test of the CERTS functions of the PCS was performed at the factory before shipping. This factory acceptance test included both island and grid-connected operation in CERTS mode. In island operation, the PCS operated alone with a real and reactive power, load bank and in parallel with a diesel generator operating in voltage and frequency droop mode. The simplicity of integrating CERTS-capable inverters with other resources operating in voltage and frequency droop was apparent at the factory acceptance test. An off-the-shelf diesel generator was integrated easily with a CERTS-capable inverter. There were no complications other than appropriately setting the droop voltage in the voltage regulator and the droop frequency in the engine governor. During the factory acceptance test, the two sources appropriately shared real and reactive power with no communication lines between the two. The speed at which the PCS adjusts its real and reactive power output on islanding also was verified, within 20 milliseconds for both real and reactive power.

The CERTS protocol allows seamless islanding because of the ability of a CERTS-capable inverter to change its real and reactive power output upon sensing frequency and voltage variations at its terminals. Seamless island tests without communication between the utility interconnection breaker and the PCS were demonstrated at the factory acceptance test, even when the PCS was required to change from discharge to charge mode or vice versa (i.e., from positive to negative real power flow).

2.2.3.3 Site Acceptance Test

The system also had to be tested at the site with all of the existing distributed energy resources and the SDS. Once the PCS and the battery enclosures were installed and integrated, island tests of the battery system and the fuel cell with a load bank were completed without including the facility load. However, these tests did not yet include parallel operation of the Santa Rita Jail diesel backup generation system. Once the battery had demonstrated reliable grid-connected operation and island operation with the fuel cell and load bank, a whole-facility island test was scheduled. This whole-facility island test had to be witnessed by local electric utility (PG&E) representatives as part of the utility's routine pre-parallel inspection process, which any conventional generator must complete. At that point all of the protective functions required by PG&E were successfully demonstrated and Santa Rita Jail was seamlessly islanded and resynchronized with PG&E for the first time. Only after this had been completed could island operation of the battery, in parallel with the facility diesel backup generation system, be tested. The controls of the diesel backup generation system had previously been modified to allow voltage and frequency droop operation. The diesel generators with their modified controls were tested and appropriate real and reactive power sharing was demonstrated. This was done at different transient conditions that included battery discharging and charging using diesel generator power.

2.2.4 Measurement and Verification

Measurement and verification results are discussed in Chapter 3: Project Results.

CHAPTER 3:
Project Results

3.1 Project Objectives: Results and Outcomes Summary

In this section the results and outcomes of the Microgrid project are summarized. Seven key objectives were achieved during this project: (1) reduce facility peak load by 50% or more, (2) reduce peak load of utility distribution feeder by at least 10% to 15%, (3) demonstrate the commercial implementation of CERTS microgrid, (4) improve grid reliability, (5) demonstrate the potential to provide grid ancillary services, (6) increase grid efficiency and security, and (7) meet critical customer reliability requirements.

All of the project objectives were considered during the system design phase and incorporated in the micorgrid design as implemented. The ability of the microgrid to meet all the project performance objectives was tested during commissioning. The commissioning process is summarized in Table 4. Since installation of the microgrid, the Santa Rita Jail site has not encountered any unplanned outages; therefore, the site has not had the opportunity to collect or measure real-world results.

Table 4: Project Objectives Summary

Project Objective	Demonstration / Commissioning Test Methodology	Results
1. Reduce Facility Peak Load by 50% or More	Comparison of the Facility's Peak Load data prior to installation of the Microgrid to the Peak Load post-installation: The microgrid's system operation was observed during a facility peak load to confirm that the distributed energy resources could offset the peak load by 50% or more.	On average the facility's peak load each month is about 2 MW. The microgrid's 1 MW fuel cell is able to reduce the site's overall demand by half. In addition to the fuel cell, the 2 MW, 4 MWh battery is programmed to dispatch energy during the period from noon to 6 PM, the same time that the facility's peak power load and peak energy consumption occurs each day. Analysis of SRJ's power quality meters' data confirmed that the combined power output of all the microgrid distributed energy resources is able to offset the facility's peak power load by 95% and the peak-time (noon to 6 PM) energy consumption by 98% (see

		Figure 12).
2. Reduce Peak Load of Utility Feeder by 10-15%	Comparison of the Utility Feeder's Peak Load data prior to installation of the Microgrid to the Peak Load post-installation: Analyze historic data of the utility feeder's load and determine how much the microgrid's distributed energy resources are able to reduce the peak load on the feeder by.	Analysis of the data collected from the utility (PG&E) of the feeder's peak load confirmed that the microgrid is able to offset the feeder's peak load by 15% (see Figure 15).
3. Demonstrate Commercial Implementation of CERTS Microgrid	Demonstrate and document that a CERTS Microgrid of this size could be designed, installed and successfully operated in a real world operational environment: Demonstrate that an advanced control system can be implemented to monitor all of the site's different distributed energy resources and to determine the most economical way of dispatching the battery.	The Santa Rita Jail microgrid is the largest CERTS microgrid implementation in the world. The project demonstrated that a commercial implementation of a CERTS microgrid is possible by successfully installing a working system at a real-world site. The ability to monitor DERs and dispatch the battery was proven in commissioning and in daily operation. At a high-security environment like SRJ, the staffs' and inmates' safety is a priority. A key benefit of the microgrid is that it enhances the facility's security by providing the site with a critical backup power source. The impact that this has on the site's safety and security is not currently quantifiable. In addition to the safety benefits, the Microgrid's battery is able to reduce annual electric utility costs by $110,000 by shifting the load from peak periods to off-peak

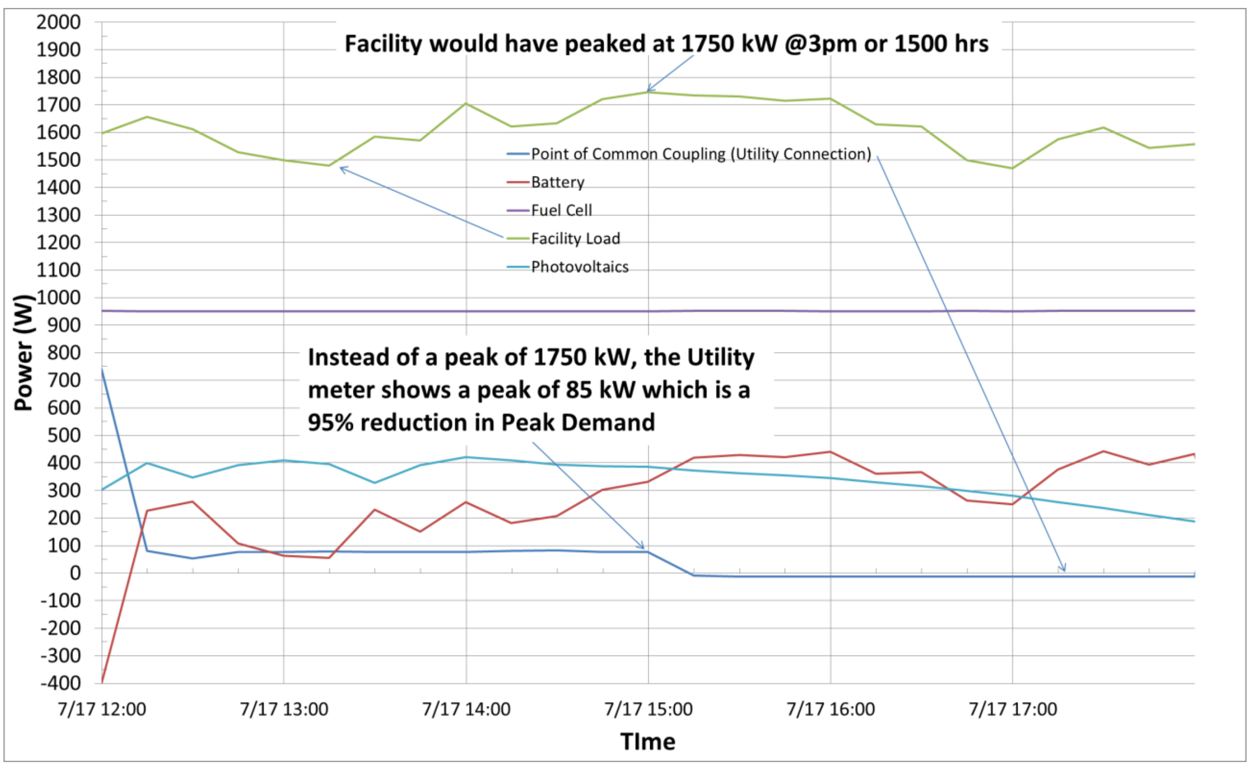
		periods.
4. Improve Grid Reliability	Demonstrate the microgrid's capability to improve the Grid's reliability through peak load reduction.	The ability to reduce the utility's peak demand was proven in commissioning (see Section 3.3.3). The utility benefits from the reduced peak power demand because this reduces transformer loss-of-life, extends equipment life and, therefore, improves overall grid reliability.
5. Demonstrate Potential to Provide Ancillary Services	Demonstrate the microgrid's capability to participate in a utility demand response program. Demonstrate excess power generated on-site can be stored at the facility rather than exported back to the utility. Demonstrate the microgrid storage component can be dispatched on command. Demonstrate the microgrid's capability to provide reactive power and voltage control support.	Section 3.6 details the various Ancillary Services the Microgrid will support The ability to store excess power generated by the DERs was proven in commissioning. The ability to dispatch the storage component on command was proven in commissioning and in daily operation. The ability to provide reactive power and voltage control was proven in commissioning and in daily operation.
6. Increase Grid Efficiency and Security	Demonstrate that the microgrid decreases the load demand on the grid: Decreasing the power flow through the utility distribution equipment leads to less utility power losses.	Reduction of demand on the feeder is documented in Objective 2. Reducing the power flow also reduces the losses on the grid. Therefore the SRJ microgrid increases the grid's efficiency.
7. Meet Critical Customer Reliability Requirements	Demonstration that the facility could island successfully and seamlessly.	Successful islanding during commissioning testing verified that the system will react as designed if a utility outage were to occur (see Appendix E for testing data).

3.2 Objective One: Reduce Facility Peak Load by 50% or More

On average, the SRJ facility's max demand each month is about 2MW. Between the 1MW fuel cell and the 2-MW, 4-MWh battery, the microgrid is able to reduce the facility's peak load by more than 50% when compared to the load without these distributed energy resources. The peak load time typically occurs during the afternoon. Since the 1MW fuel cell is run continuously, the max demand of 2MW can be reduced by half at this time. In addition, from noon to 6 P.M. the battery system is discharged to further reduce the max demand. These two pieces are able to contribute to reducing the facility's peak load by more than 50%. Figure 12 shows the SRJ microgrid's on-site power generation on the day of July 17th, 2012 from noon to 6 P.M, the same time that the facility's peak power load and peak energy consumption occurs each day. The graph shows that the total contribution of the battery, fuel cell, and photovoltaic system is able to reduce the facility's peak power load by 95% (reduced from 1750 kW to 85 kW) and the peak-time (noon to 6 PM) energy consumption by 98% (reduced from 10,221 kWh to 228 kWh) .

Furthermore, since the battery maintains the facility's power during utility disturbances, the fuel cell is now able to operate more reliably. Prior to installation of the microgrid, any loss of facility power would cause the fuel cell to trip offline. Once tripped, restoration of the fuel cell took up to 18 hours. The microgrid improves the availability of the fuel cell and this was proved during the commissioning test shown in Appendix E.

Figure 12: Reduced Facility Peak Load



Source: Chevron Energy Solutions

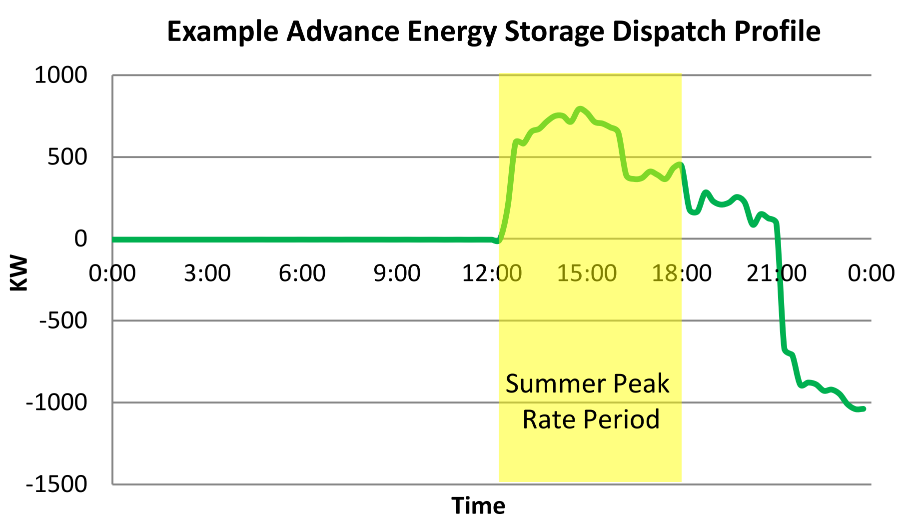
3.3 Objective Two: Reduce Utility Feeder Peak Load by 10 to 15%

The Microgrid project is able to reduce the peak demand of the utility distribution feeder by 15% with the use of new and existing distributed energy resources. The scope of the project included installation of a 2-MW, 4-MWh advanced energy storage (AES or battery) system and an overarching control system termed Distributed Energy Resources Management System (DERMS). DERMS integrates the AES with the existing facility generation resources – a 1-MW fuel cell, 1.2-MW solar PV system, 11.5-kW wind power system, and two 1.2-MW emergency diesel generators. This section details the contributions of the individual distributed energy resources to lowering the utility feeder peak load.

3.3.1 Advanced Energy Storage

The DERMS algorithms intelligently dispatch the 2-MW, 4-MWh battery system to maximize the utilization of the AES during peak electric rate periods, which correspond to high feeder demand loading. DERMS predicts the facility energy usage for the peak period, evaluates the available AES capacity, and then discharges the AES power to minimize the facility demand throughout the period which in turn reduces the feeder demand. Figure 13 is an example of the AES operation during the summer peak period. Note that the kW measurements are negative during the AES charge periods and positive during discharge.

Figure 13: Example AES Profile



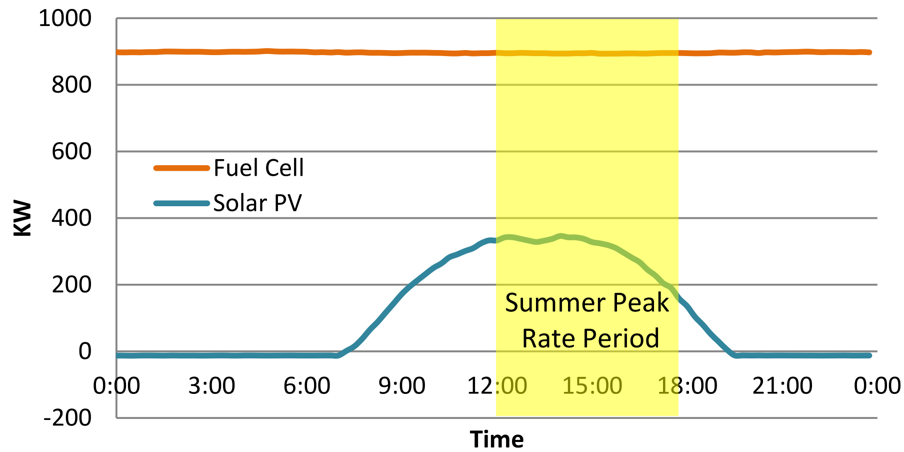
Source: Chevron Energy Solutions

3.3.2 Fuel Cell, Solar Photovoltaic and Wind

The existing distributed energy resources also contribute to the reduction in utility peak feeder loading. The fuel cell has a constant 24-hour output of approximately 900 kW. The solar PV output varies with the solar irradiance. The peak PV power output does not necessarily correspond with the peak utility feeder loading, however PV produces power at some level during higher feeder loading periods. The wind power output is also variable, but there is no correlation to peak feeder periods. Since the diesel generators provide backup power when the facility is islanded from the utility grid and are not used when the facility is connected to the grid, they do not provide demand reduction advantages.

DERMS does not directly control the on-site generation of the fuel cell, solar PV or wind; however, it does takes into account their availability and real-time output. DERMS adjusts the AES operation schedule and on-peak output to minimize facility demands. Figure 14 is an example of the fuel cell and PV output during a summer peak period. Note that the current solar PV system is operating close to half of its installed rating of 1.2 MW. When the full system is on line, the peak PV output would normally be closer to 1,000 kW.

Figure 14: Example Fuel Cell and Solar PV Profile



Source: Chevron Energy Solutions

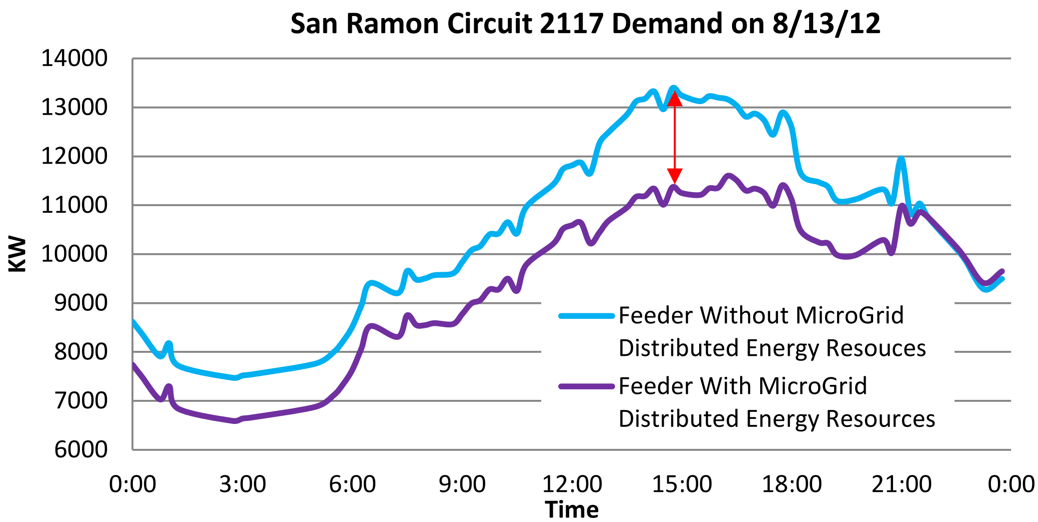
3.3.3 Example of Total Demand Reduction on Peak Feeder Loading

To evaluate the actual impact of the facility's distributed energy resources on the utility feeder under peak loading conditions; a sample 24-hour period was analyzed. PG&E, a key partner in the demonstration project, provided feeder demand data for one of the highest peak loading days in August. The month of August, because of high ambient temperatures, is typically the month when the peak yearly load for utility feeders occurs.

Figure 15 shows the impact that the Microgrid distributed energy resources has on the PG&E San Ramon Circuit 2117, on August 13, 2012, a day when the feeder was under peak loading conditions. PG&E San Ramon Circuit 2117 is the feeder that serves Santa Rita Jail. In the figure, the purple line represents the load on the feeder when it has the support of SRJ's Microgrid distributed energy resource contributions and the blue line represents the feeder's load when it does not have the Microgrid distributed energy resource contributions. The figure shows that if the Microgrid resources were not available, the feeder would have peaked at 14:45 with a demand of 13,395 kW. However, with the Microgrid resources available, the demand was reduced by 2,023 kW or 15% of the total feeder load.

The individual distributed energy resources contributions are listed in Table 5. This example day meets the goal of 15% peak demand reduction. If the solar PV was at full production, the demand reduction may have been larger, but it is capped at the facility load. DERMS will dispatch the AES to reduce the facility import to zero, but will not export power to the grid.

Figure 15: Example Peak Feeder Demand and Microgrid Impact



Source: Chevron Energy Solutions

Table 5: Distributed Energy Resource Contributions to Demand Reduction

Resource	Output	% of Feeder Demand
AES	792 kW	5.9%
Fuel Cell	894 kW	6.7%
Solar PV	337 kW	2.5 %
Total	2,023 kW	15.1%

Source: Chevron Energy Solutions

3.3.4 Additional Demand Reduction Opportunities

In addition to the distributed energy resources detailed in the previous sections of this report, 277 kW of tracking solar PV was installed after DERMS and the AES were commissioned. It is not currently being monitored by DERMS, but could result in an additional 1%–2% of peak demand reduction.

Furthermore, the utility could further lower its feeder loading by a demand response request from the utility in return for compensation of the utility bill. The demand response could be accomplished in two ways: (1) the facility would change its AES dispatch strategy and set discharge rate to meet the utility request, or (2) the facility could manually operate its load shed system, a system that allows the facility to respond by shedding non-critical loads, decreasing the facility demand.

3.3.5 Conclusions

The testing, commissioning and monitoring of the AES and DERMS confirmed that the new system is able to utilize all on-site available generation sources to reduce the facility's demand during peak summer loading periods. The data and system performance will continue to be analyzed to determine if the DERMS algorithm can better optimized to improve the utilization of the AES and thereby further reduce the facility and utility feeder peak loading.

3.4 Objective Three: Demonstrate the Commercial Implementation of a CERTS Microgrid

3.4.1 CERTS Microgrid Introduction

The Alameda County Santa Rita Jail Microgrid project is a commercial demonstration of a Consortium for Electric Reliability Technology Solutions (CERTS) Microgrid. CERTS was developed and is licensed by the University of Wisconsin. The Consortium is pioneering the use of microgrids as an alternative method of integrating small-scale distributed energy resources (DERs) into electric distribution networks. Traditional approaches were focused on safety and would require DERs to instantaneously disconnect in the event of a system outage in order to minimize the consequences on grid performance. By contrast, microgrids are designed to operate independently. They usually operate connected to the grid, but can island from it if necessary in order to maintain performance or to reduce cost. The focus of this report was on Santa Rita Jail's CERTS Microgrid and its ability to operate independently.

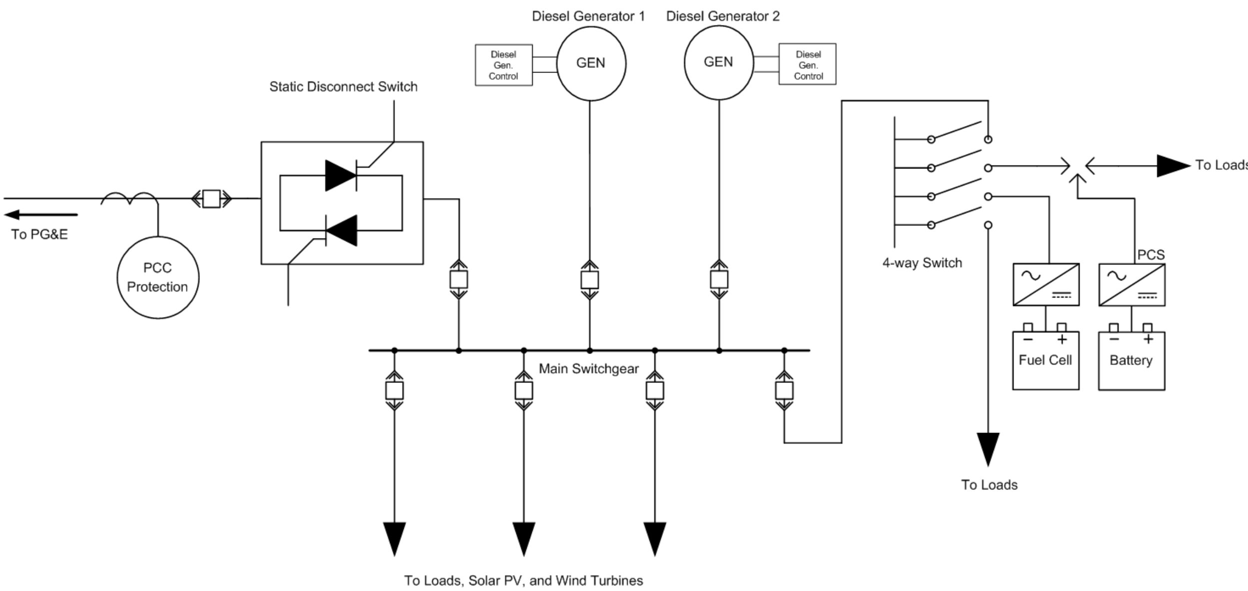
3.4.1.1 CERTS Microgrid System Objective

The CERTS Microgrid is a relatively new approach to integrating DERs. The conventional approach to DERs is outlined in the Institute of Electrical and Electronics Engineers (IEEE) Draft Standard P1547 for Distributed Resources Interconnected with Electric Power Systems and focuses on ensuring that interconnected generators will shut down automatically if there is a problem on the grid. By contrast, the CERTS Microgrid is designed to seamlessly island from the grid and to automatically reconnect to the grid once a problem has been resolved. [11] The Santa Rita Jail Microgrid has this ability.

3.4.1.2 CERTS Microgrid System Functionality

The SRJ Microgrid project integrated multiple generation resources located at the facility. These resources include a 2-MW, 4-MWh advanced energy storage (AES or battery) system, 1-MW fuel cell, 1.2-MW solar photovoltaic system, 11.5-kW wind power system, and two 1-MW emergency diesel generators. Figure 15 is a one-line diagram of the Santa Rita Jail Microgrid showing all of the generation resources. The Microgrid is controlled by an overarching control system, Distributed Energy Resources Management System (DERMS). When a disturbance to the utility grid occurs, the automatic disconnect switch enables the SRJ Microgrid to island in eight milliseconds or less at the point of common coupling (PCC). This would allow for all generations and loads to stay on line. In the event that the Microgrid islands from the grid, the frequency and voltage are controlled with the battery system in CERTS mode. If the grid experiences an extended outage, the two 1-MW emergency diesel generators can come on line to support the renewable generations. In this case, the frequency and voltage are controlled with the battery and diesel generators in CERTS mode. Both the battery and diesel generators are CERTS capable. The SRJ Microgrid complies with the CERTS requirements for frequency droop, voltage droop, and passive synchronization.

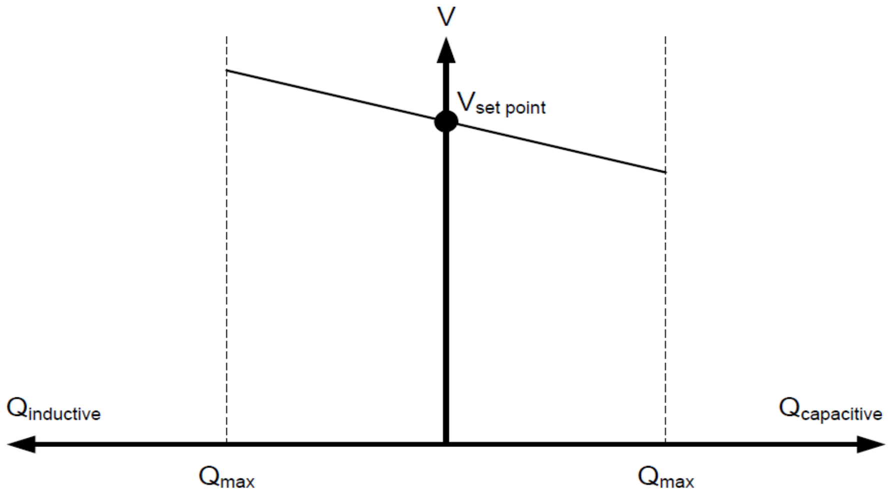
Figure 15: Santa Rita Jail Microgrid One-Line Diagram



Source: Chevron Energy Solutions

Voltage regulation is necessary for reliability and stability when integrating large numbers of DERs into a microgrid. The DERs can create a large amount of circulating reactive current which can lead to voltage and/or reactive power oscillations. This problem is alleviated through the use of a voltage vs. reactive power droop controller. As the current generated by the DERs becomes more capacitive, the local voltage setpoint is reduced. Conversely, as the current becomes more inductive, the voltage setpoint is increased. [11] The function of the basic controller is shown in Figure 17.

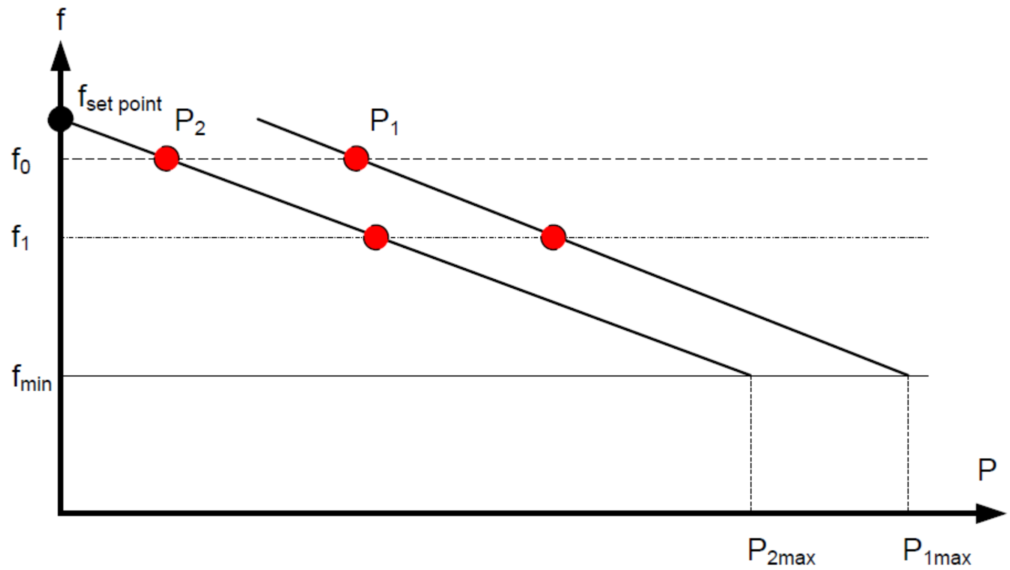
Figure 17: Voltage Setpoint with Droop



Source: Chevron Energy Solutions

When the microgrid is in island mode there can be slight errors in the frequency generation of each inverter. After the microgrid separates from the grid, the voltage phase angle of each DER changes resulting in a reduction of the local frequency. Figure 18 is an example of the power vs. frequency droop control. In this example, two DERs have two different ratings of P_{1max} and P_{2max}. A change in power demand leads to two different operating frequencies for these two sources. When that happens, the two frequencies tend to drift towards a single overall lower frequency value (f_1). The droop control ensures that both systems are at rated power at the same minimum frequency (f_{min}). Since droop regulation decreases the microgrid's frequency, a frequency restoration function must be included in each of the DER controllers. [11] The frequency restoration function works by adjusting the power output and input controller of each DER according to the droop curve to get the frequency back into a safe operating range. The CERTS Microgrid at SRJ has a control system in place to protect against frequency droop.

Figure 18: Power vs. Frequency Droop Control



Source: Chevron Energy Solutions

3.4.1.3 CERTS Microgrid Advantages

The CERTS protocol is a powerful tool for simplifying the integration of distributed generation resources. It provides guidelines for the factory and site acceptance tests, and it allows for the use of off-the-shelf generation control equipment.

A significant advantage for CERTS is that it allows asynchronous generation sources (inverters) to integrate with and operate as synchronous generators. This allows DERs to behave similarly to the large utility grid, allowing for generator sources to support the electrical demands in frequency, voltage and power (real and reactive).

3.4.1.4 CERTS Microgrid Limitations

An inherent characteristic of a CERTS system is that the frequency is continuously shifting back and forth; this leads the voltage source generators to continuously track this frequency. At Santa Rita Jail, this characteristic led to trickle charge and discharge of the battery. Battery trickle charge is less accurate in CERTS voltage-source mode than in current-source mode. It also leads to issues with maintaining battery system control at 0% and 100% state of charge given this continuous tracking of frequency.

3.4.1.5 CERTS Microgrid Scope, Components and Integration

In order to demonstrate a CERTS Microgrid that incorporates both large scale storage and renewables this project required the use of custom designed software for the DERMS component and custom built or specially modified hardware for major components other than the Advanced Energy Storage components. The project also required significant engineering effort in integrating the various components into a CERTS compliant system. In other words the commercial scale of this project required the breaking of new CERTS ground. This project proved that a Microgrid developer can be equipment agnostic and in fact change technologies mid-stream if required and still integrate and operate successfully.

Future projects following CERTS Microgrid specifications can result in significant cost savings due to the simplified integration and the ability to be equipment agnostic; the developer is not locked into any one manufacturer or technology. Additionally a CERTS Microgrid enables CERTS-capable generators to interconnect without the need of a supervisory generator control system. CERTS therefore not only offsets the cost of developing a real-time, highly sophisticated software control system, but, by eliminating this element, improves the reliability and operability of generators. In addition, the system can control distributed energy resources to save utility costs as shown in section 3.4.2.3.

Given the current cost of large scale storage, a major component in this project, it appears the most significant benefit of this CERTS Microgrid is security and reliability of the physical plant. The dollar value of avoiding a blackout event even momentarily at a high risk facility such as Santa Rita Jail is not quantifiable within the scope of this project. The saving from reduced demand charges and participation in demand response programs potentials are documented elsewhere in this report, but are currently seen as an adjunct benefit.

3.4.2 DERMS Introduction

The Alameda County Santa Rita Jail Microgrid project integrated multiple generation resources at the facility. The unique mix of resources provided the jail with the opportunity to maximize the operation of these resources utilizing innovative methods. One of the goals of the Microgrid project was to ensure optimum usage of all available generation resources to minimize utility costs. The scope of the project included installation of a 2-MW, 4-MWh advanced energy storage (AES or battery) system and an overarching control system termed Distributed Energy Resources Management System (DERMS). DERMS was designed and developed by Chevron Energy Solutions. It integrates the AES with the existing facility generation of a 1-MW fuel cell, 1.2-MW solar PV system, 11.5-kW wind power system, and two 1-MW emergency diesel generators. The DERMS has the capability to monitor all generation resources and incorporates an innovative decision engine to determine how to economically dispatch the AES. This section focuses on the DERMS decision engine and dispatch strategy of the AES.

3.4.2.1 DERMS System Objective

The DERMS algorithms evaluate the electric utility rates and available generation sources and dispatch the AES to minimize demand and energy costs. The local electric utility rate structure has both a demand (kW) and an energy (kWh) cost component. The rate is further broken down into Time-of-Use (TOU) categories based on time of year and time of day. The most expensive rate occurs during the summer peak hours and the least expensive rate occurs during the winter off-peak or night hours. Additionally there is a monthly maximum demand charge. DERMS recognizes the rate period the system is currently operating in and controls the AES based on the following philosophy:

- **Summer Peak**: Reduce demand and energy costs
- **Summer and Winter Partial Peak**: Manage TOU and monthly maximum demand costs
- **Summer and Winter Off-Peak**: Minimize monthly maximum demand costs

3.4.2.2 DERMS System Components and Functionality

Innovative Decision-Making Engine

DERMS has a different dispatch strategy for each of the rate categories defined in Section 3.4.2.1.

For each time period**,** DERMS forecasts the energy usage for the period and the status of the on-site energy sources including the AES status. DERMS applies its innovative algorithm in evaluating the multiple economic criteria of energy and demand costs and operates the battery to minimize the monthly utility costs. In addition to the embedded forecasting and simulating functionalities in DERMS, the system has a unique design feature as it continuously captures actual real-time information from the metering and monitoring infrastructure. DERMS utilizes this information in its battery dispatch decisions, ensuring that the actual realized operation is as close as possible to the optimized simulated strategy.

Data Monitoring and Metering

DERMS monitors several points within the system to optimize the AES and other generation utilization. The DERMS inputs are detailed below:

Power Flow at the Point of Common Coupling (PCC): The PCC is where the utility meter is located. DERMS manages the facility demand and energy usage at this point.

Solar Photovoltaic Power Output: The photovoltaic power output varies with the solar irradiance. DERMS predicts the solar photovoltaic output based on recent historical data and updates the predicted solar output based on real time feedback.

Fuel Cell: During normal operation, the fuel cell power output is flat 1MW and supplies a significant portion of the load. In the event of the fuel cell tripping offline, DERMS will adjust the AES dispatch strategy to account for large change in generation availability.

Wind Power Output: The wind power output supplies a small percentage of the total system load. It is monitored to give a more accurate view of the system operating conditions, but is not used directly in the battery dispatching logic.

Battery State of Charge (SOC): DERMS uses the battery state of charge (SOC) to determine the available capacity to charge and discharge based on generation sources, historical load date, and time left in the current rate period.

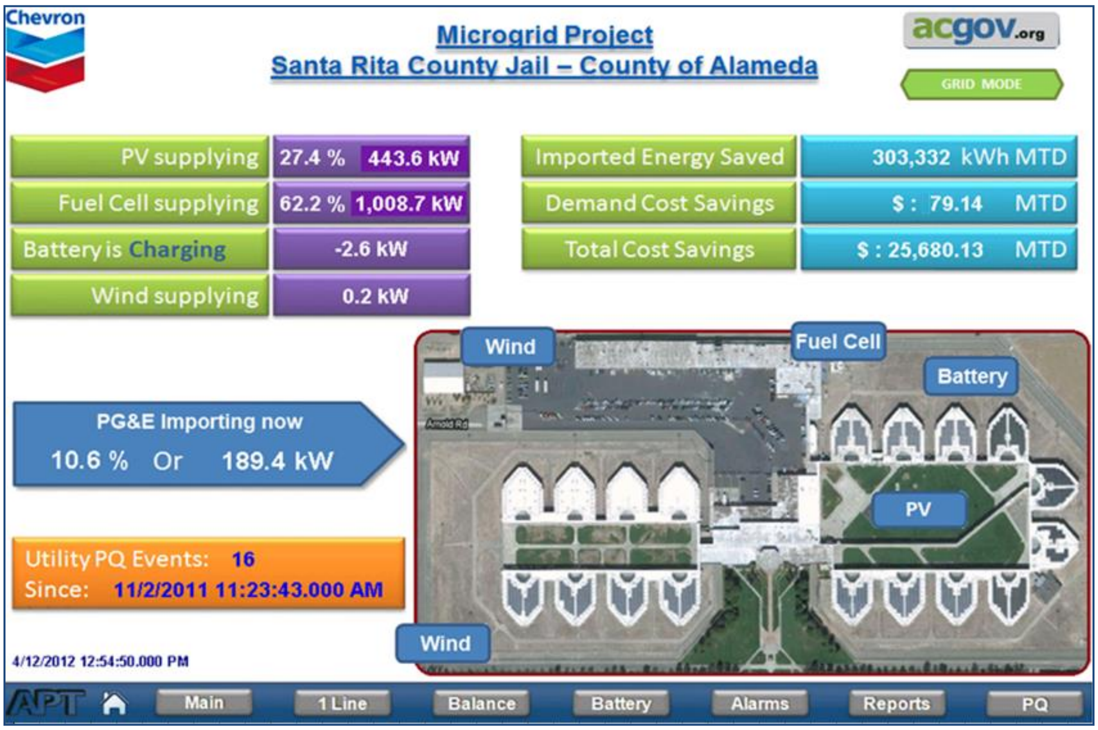
DERMS Human Machine Interface (HMI)

There are several DERMS HMI screens that allow the operator to understand how the system is operating real time and the performance and cost savings for the month.

Figure 19 is a screen shot of the main system overview HMI screen. It shows the state of all of the generation sources including the utility supply. The screen also shows the calculated utility costs savings from the AES, fuel cell, solar photovoltaic and wind power for the month.

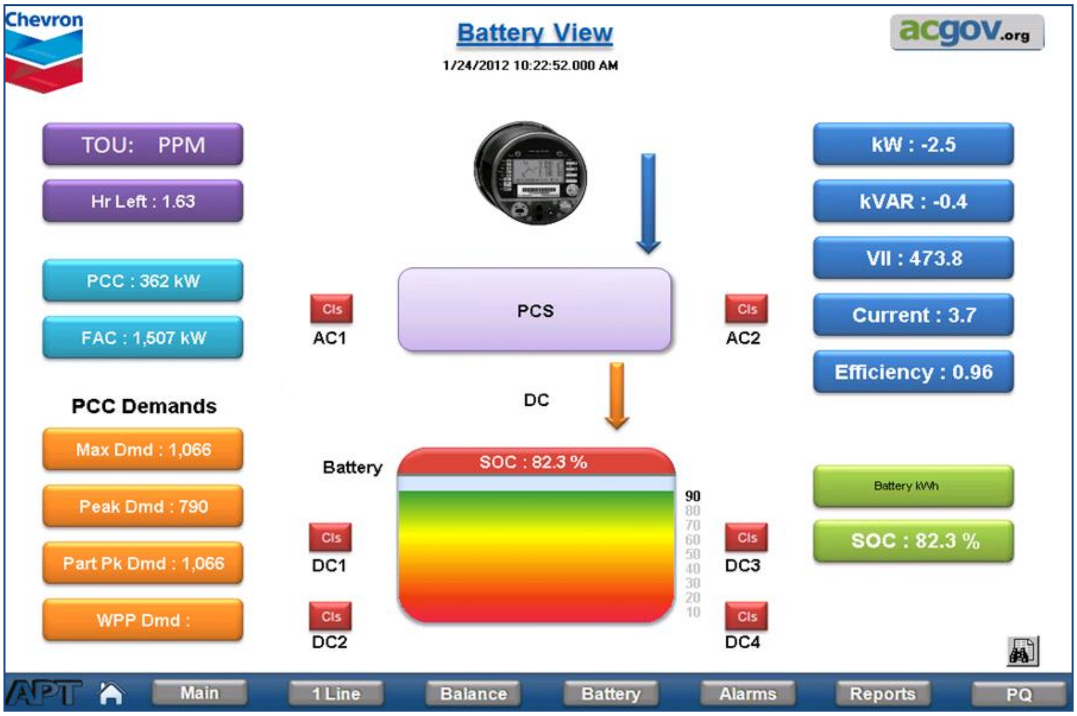
Figure 20 is a screen shot of the AES overview. The screen contains all of the information DERMS uses to determine AES dispatch strategy. For example, in this overview the system is operating in the summer partial peak morning (PPM) period with 1.63 hours remaining and 82.6% SOC. DERMS knows the monthly maximum demand and partial peak demand are currently at 1066 kW and it will try to charge or discharge the AES as needed such that the power flow at the PCC does not exceed 1066 kW.

Figure 19: HMI Screen of System Overview



Source: Chevron Energy Solutions

Figure 20: HMI Screen of AES Overview



Source: Chevron Energy Solutions

3.4.2.3 DERMS Estimated Benefits

Based on the Santa Rita Jail facility's historical load and generation profiles, the DERMS algorithms estimate that installation of the AES and DERMS will reduce annual electric utility costs by $110,000 (based on PG&E tariff E20P, effective March 1, 2012) just by shifting the load from peak periods to off-peak periods. This estimate does not include savings provided by storing excess power generation. Table 6 shows the rate categories under which the savings would be captured. It is estimated that over 75% of the savings would be generated during the summer period when rates are highest. The summer and winter energy savings are net of savings from discharging the AES at peak or partial peak hours and costs of charging the AES during off-peak hours.

Table 6: Savings by Rate Category

Rate Category	% of Savings
Summer Max Demand	15%
Summer Peak Demand	45%
Summer Partial Peak Demand	3%
Summer Energy	14%
Winter Max Demand	20%
Winter Partial Peak Demand	1%

Winter Energy	2%

Source: Chevron Energy Solutions

3.4.3 Conclusion and Next Steps

The system cost including the Static Disconnect Switch and Battery systems was approximately $12MM. This cost includes a significant portion which would not be bourne by subsequent installations such as research and development and costs associated with the integration of brand new technologies. The testing and commissioning of the AES and DERMS has confirmed that the new system is able to utilize all available on-site generation sources to shift the facility's utility energy consumption from high cost periods to low cost periods. The facility data and system performance will continue to be analyzed to compare the estimated savings with the actual savings. That analysis will also help in recommending new DERMS setpoints, especially the maximum and minimum AES SOC used in the dispatch algorithm. The current setpoints leave a margin of capacity to account for the difference between the predicted and real-time load and generation profiles and provide the AES available capacity to be used in the event of a utility power outage. Refining these values will further optimize AES usage during the various rate periods. Additional benefits recognized but not quantified are the costs benefits to SRJ by avoiding outages and power quality events. These reliability related benefits may be substantially greater than the savings realized by the Utility costs savings but are too complicated for the customer to calculate and were therefore left out of this economic analysis.

Table 7 shows the cost of researching and developing the Microgrid plus the costs of acquiring and installing the equipment (including the large scale storage system) and the control mechanisms. It excludes the costs of the pre-existing renewable energy resources. The annual costs savings are the result of utilizing the Microgrid in conjunction with those pre-existing energy resources. With an estimated annual demand and energy cost saving of $110M, the SRJ Microgrid project would have a payback period of 109 years.

Table 7: SRJ Microgrid Project Payback Period

Capital Cost of Microgrid Design R&D, Equipment, and Installation	$12MM
DERMS Estimated Annual Demand and Energy Cost Savings (Using the battery to shift the load from peak periods to off-peak periods)	$ 110M
Payback Period	109 Years
Facility Benefit of Seamless Islanding and Restoration	Not Quantifiable

Even though the microgrid project has a prolonged payback period, it should be remembered that the Santa Rita Jail site is a high security location and maintaining energy integrity, i.e. keeping the lights on via seamless islanding and restoration has precedence over energy cost savings. The dollar value of seamless islanding is not quantifiable within the scope of this project

The testing and commissioning of SRJ's Microgrid demonstrated the DER "plug-and-play" capability of a CERTS Microgrid at a commercial site. The Microgrid was able to effectively integrate its various energy resources and energy storage system. The project was also successful in demonstrating the potential for large commercialization of CERTS Microgrids to future target customers with demand for reliable power. The data and system performance will continue to be monitored. Islanding and re-syncing of the Microgrid is infrequent and only happens once or twice a year. These occurrences will be monitored and the system's synchronization and power sharing performance will be examined.

3.5 Objective Four: Improve Grid Reliability

The grid that SRJ is connected to is part of a 21kV planning area serving a mixture of Residential, Commercial, Industrial and Agricultural loads. Typically, PG&E will utilize up to 95% of the Area Capacity before undertaking a project to increase capacity. The peak load for the area will typically occur on the third or fourth consecutive day of heat during a hot summer day and will typically last a couple of hours. The distribution system, during this time of stress, undergoes an increase in loss of life for transformers and conductors operating at higher temperatures. This increase in equipment loss of life is due to both the higher temperature and the higher load. Equipment failures often occur during these times of high stress and the likelihood of failure is exacerbated the more frequently the equipment undergoes these conditions.

Utility peak demand was reduced by 15.1% (see section 3.3.3 for the data) which reduces the likelihood of a utility outage caused by feeder overload. This reduction in the feeder's peak demand was achieved through the use of DERMS. Since DERMS has the ability to control all of the site's distributed energy resources, it therefore has the ability to dispatch the resources at periods when it would most benefit the utility. In particular, the battery's stored power can be dispatched to offset the mid-day peak demand period. The utility is benefited by the reduced peak power demand because this reduces transformer loss of life and extends equipment life and therefore improving overall grid reliability.

In the future, grid reliability indices like System Average Interruption Duration Index and System Average Interruption Frequency Index can be compared between grid planning areas with and without Microgrid to better measure the benefits. Because SRJ has not yet experienced a Utility outage, there is not sufficient data to track the grid reliability benefits. However, it is believed that a better measure of grid reliability improvements will come from Utilities and their experience with Microgrids.

3.6 Objective Five: Demonstrate the Potential to Provide Grid Ancillary Services

In addition to the utility cost savings calculated in Section 3.4.2.4, the new system provides other potential benefits to the jail. Prior to the installation of the AES and DERMS, the utility required a reverse power relay preventing the fuel cell and the photovoltaic system from feeding power into the utility grid. If the on-site generation exceeded the load, the reverse power relay would trip the photovoltaic system first and then the fuel cell. The fuel cell requires 18 hours to restart and ramp to full output during which time the facility would have to purchase utility power. With the new system, the excess power can be used to charge the AES and fully utilize on-site generation.

In addition, DERMS provides the jail with the capability of responding to utility demand response requests. By owning a working microgrid system, Alameda County is able to participate in the utility's demand response program. There are instances when the utility may want the SRJ facility to reduce their load demand on their feeder for specific periods of time. The utility may contact the county and ask if they are able to help reduce their demand by discharging their battery system. As an incentive for participating in the demand response program, the county will receive a rebate on their monthly utility bill. The ability to participate in PG&E's demand response program is an ancillary benefit of the SRJ microgrid. Alameda County is considering participation in PG&E's demand response program, but as of the completion of this project has not yet participated; therefore, there is no data available to quantify the benefit of this ancillary service.

In addition to the demand response capabilities, the microgrid also has the ability to provide the grid with reactive support. The battery's power conversion system is capable of providing up to 1.5 MVAR of reactive power/voltage support. Even though the facility does not have a need to provide much reactive power support through the power conversion system, it has the capability to provide additional reactive power support to the grid if needed.

3.7 Objective Six: Increase Grid Efficiency and Security

In general, electrical distribution equipment performs more efficiently when the equipment is not being utilized near its rated capacity. The greater that a piece of equipment is being utilized, the more inefficient it becomes. This is because the natural resistance of the equipment, which is what causes system losses, the losses from these resistances is amplified when there is a greater amount of current flowing through the equipment.

The addition of the SRJ microgrid has helped reduce the demand on the utility's feeder. By reducing the demand on the feeder, the microgrid is reducing power flow, and therefore losses, on the feeder. With reduced power losses, the grid efficiency is increased.

During the project implementation it became clear that the Utility was not prepared to integrate the SRJ facility's SCADA system with the Utility's SCADA system. The DOE and Chevron agreed to remove SCADA from the scope of the project objectives. Therefore, this project did not address grid security.

3.8 Objective Seven: Meet Critical Customer Reliability Requirements

Customer Reliability Requirements were an important factor for why SRJ wanted a Microgrid. Since the SRJ microgrid has been installed and commissioned, there have been no outages due to grid instability. However, the SRJ Microgrid has been successfully islanded during commissioning tests which verifies the system will react as designed if utility outages were to occur. (See Appendix E for results.)

The main objective of the tests was to determine how the Microgrid would react to Utility disturbances under a variety of changing scenarios for the Microgrid and the Facility. A Utility disturbance was simulated by opening the voltage signal from the Utility to the SDS control board. While islanded, a variety of scenarios, including simulating low and high battery state of charges, were simulated in order to observe the diesels generators turn on, charge the battery with diesel power and turn off when the battery reached a pre-set state of charge. While islanded, the Microgrid is capable of charging the battery using the diesel generators if the battery's state of charge is too low. The Microgrid's islanding operation was also tested with and without the Fuel Cell, with and without the PV system and with the load shedding system.

During the early stages of testing it became apparent that the Facility's existing load shed system was not adequate. Some loads would trip when they didn't have to and others would stay on when they should trip. Separate from the DOE grant, but very important to the success of the Microgrid, Alameda County contracted CES to upgrade their existing load shed system to a more responsive and selective system. The results of the commissioning and testing were very successful especially in regard to the Utility restoration. In each case, returning the voltage signal to the SDS would simulate Utility restoration and the SDS would resynchronize and close. These same tests were performed across the Main Breaker, M1, also with great success.

According to Santa Rita Jail Captain Bert Wilkinson in an interview prior to installation of the Microgrid:

> *"With about 4,000 inmates housed in eighteen housing units, it is easy to understand that any interruption in the electricity potentially puts our deputies in harm's way. . . When the lights go out because of a power outage, those few seconds it takes for our emergency generators to bring the lights back on seems like an eternity to a deputy who is in the process of moving inmates within the jail."*

During the commissioning process the entire facility was islanded a number of times. Even though the staff had advance warning of the planned time for the islanding events, they were not able to detect an interruption when islanding occurred. According to Alameda County's SRJ Microgrid Project Manager, Matt Muniz, in an interview following the commissioning testing:

"Reliability to us means: being able to maintain jail operations undisturbed by power interruptions. Any disruption in jail electrical operations can have dire consequences. The Microgrid's islanding capability was tested and commissioned in the jail environment, live and real-time. During testing, islanding was completely transparent; even though we knew when islanding would occur, we didn't see the lights flicker and our sensitive electronic equipment was not disturbed. This transparent disconnection/reconnection to and from the main grid will eliminate those very risky blackout events that had occurred prior to the installation of the Microgrid."

CHAPTER 4: Technology Transfer Activities

4.1 NREL (National Renewable Energy Laboratory)

The object of these reports was to model the microgrid and estimate potential cost savings, and then to analyze data over a two year period of operation of the microgrid, in order to calculate actual cost savings and compare to potential cost savings, and suggest potential operational strategies to further reduce energy costs at the jail. See Appendix A. There are two NREL documents, one examining the system performance during the year 2012 and another for the year 2013 which also compares the differences between the two operating years.

4.2 IEEE (Institute of Electrical and Electronics Engineers)

The Consortium for Electric Reliability Technology Solutions (CERTS) Microgrid concept captures the emerging potential of Distributed Energy Resource (DER) using an automatous plug-and-play approach. The sources can operate in parallel to the grid or can operate in island, providing high levels of electrical reliability. The system can disconnect from the utility during large events (i.e., faults, voltage collapses), but also may disconnect intentionally when the quality of power from the grid falls below certain standards. CERTS Microgrid concepts have been demonstrated at the Alameda County Santa Rita Jail in California. See Appendix B for paper published on IEEE Transactions on Smart Grid, Vol 5, No. 2, March 2014.

4.3 LBNL (Lawrence Berkeley National Laboratory)

The extent to which that jail is capable of islanding is principally dependant on the energy capacity of the battery—is one focus of this investigation. Also presented are overviews of the DER currently installed at the jail, as well as the value it provides by offsetting the purchase of electricity under the current Pacific Gas & Electric (PG&E) tariff. See Appendix C for document published by Lawrence Berkeley National Laboratory, "Integration & Operation of a Microgrid at a Santa Rita Jail."

4.4 University of Wisconsin-Madison

The issues addressed in this report are related to the problems resulting from a mixed system. In this case a mixed system implies a mixture of CERTS compliant components such as the storage and the gensets working together with fuel cell and PV sources which cannot contribute to the control of voltage or frequency. Basically in island operation these sources depend on the storage to regulate voltage and frequency in addition to load tracking. See Appendix D for paper published by the University of Wisconsin-Madison, “Studies on the Santa Rita Jail CERTS Microgrid.”

CHAPTER 5: Lessons Learned and Conclusions

As a demonstration project it is important to share the key findings and lessons learned that arose during the project for future systems to improve upon their design, integration or performance. The testing, commissioning and operation at Santa Rita Jail has proven CERTS to be a powerful tool for simplifying the integration of distributed energy resources. Only minor modifications in the existing diesel backup generation systems were needed to allow it to operate in parallel with the CERTS-capable battery. The voltage and the frequency at the terminals of the equipment provide all the communications required for the system to operate and share real and reactive power between conventional generation and the large-scale energy storage system appropriately. This characteristic of the CERTS protocol not only adds simplicity, but also improves reliability. When functions beyond simple sharing of real and reactive power are required, like charging or discharging of the large-scale energy storage system at a certain level, at a certain time, these are achieved with simple programming and low speed communication between off-the-shelf hardware designed to control conventional generation that needs to be part of the generation system anyway. This results in lower integration cost and lower communication/control hardware and software cost compared to systems that do not use the CERTS protocol and droop operation, and require sophisticated, high-speed communications among the different elements of the system.

In a Microgrid system that has so many functions, an overarching control system such the Distributed Energy Resources Management System (DERMS) employed on this project is an important component, even when CERTS-capable distributed energy resources can operate without necessarily having communication among them. DERMS should include an archive system to provide the information needed to make continued improvements on the system. For this project, the DERMS records information including energy consumption by feeder, real and reactive power flow, power quality monitoring, and battery condition. After reviewing archived information, the settings that control grid-connected and island operation were adjusted to improve the benefit the battery provides to the facility. There is still much to be learned about maximizing the benefit that a battery system can provide. The DERMS archive system will continue to provide information to support additional improvements.

The SDS was used as a fast disconnection point from the PCC, however, until utilities are more familiar with SDSs and standards are further developed for their use as PCC disconnection devices, conventional equipment like electromechanical breakers and conventional protective relays will continue to be used to satisfy utility interconnection requirements for Microgrids.

On the battery side, the integration of the battery enclosures and PCS has to be carefully managed. The Battery Management System (BMS) that manages and monitors the condition of the batteries in the battery enclosures needs to communicate with the PCS to report state of charge (SOC), charge and discharge limits, malfunctions, alarms, etc. It may be a challenge to achieve reliable communication in the noisy environment created by fast switching power electronics in the PCS and it made copper communication wiring impossible. Fiber optic communications to the batteries and to the PCS was needed. The battery system in this project is made up of many individual cells. The BMS must balance the charging and discharging of the individual cells. Annual recalibration and balancing of the cells are required to access the full kWh capacity of the Battery Systems. Also, accurate SOC reporting is key in a battery system that is charged and discharged daily for rate arbitrage, but also needs to leave energy available for power quality functions. SOC reporting is based on DC Voltage for the high and low ends of the charge. However, in the middle operating range, kWh must be monitored to accurately calculate SOC.

In order to enhance the system performance and reliability in island mode, a new load shed system was installed at the facility. The previous system only allowed the high priority loads to remain online when separated from the grid. The new scheme will maximize the connected loads that can be supported by available generation, which is the entire facility in most cases. This is made possible by the added ability to add or shed individual loads, solar photovoltaic, fuel cell, and diesel generation based on the battery state of charge. It is critical to keeping the battery operating with safe margins and to ensure the reliability of the Microgrid island operation, especially at high and low battery state of charge. The system will also have traditional frequency-based shedding. In grid-connected mode, the system has the ability to accept an external load curtailment command as a part of a utility demand-side management program.

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APPENDIX A:
NREL: Santa Rita Jail Microgrid Report

Santa Rita Jail Microgrid Report

W. Kramer, D. Martin, G. Martin
National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.
Technical Report for Subtasks 23.1-A and 23.1-B
Santa Rita Jail Project
June 2013

Contract No. DE-AC36-08GO28308

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Prepared under Task No. DP08.9301

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Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 1

Acknowledgements

The authors would like to thank the U.S. Department of Energy, Alameda County, Chevron Energy Solutions, Lawrence Berkeley National Laboratory and the following people for their support including: Merrill Smith, Matthew Muniz, Eduardo Alegria, Osama Idrees, Anthony Ma, Craig Gee, Furqan Saleemi, Erin Minear, Chris Marnay, Sam Sprik, Chris Ainscough, Brian Mollohan, and Ben Kroposki.

List of Acronyms

CERTS	Consortium for Electric Reliability Technology Solutions
DOE	U.S. Department of Energy
HOMER	Hybrid Optimization Model for Electric Renewables
NREL	National Renewable Energy Laboratory
PCC	Point of common coupling
pf	Power factor
PG&E	Pacific Gas and Electric Company
PV	Photovoltaic
VAR	Volt Ampere Reactive

Executive Summary

The Santa Rita Jail is located in Dublin, California within Alameda County. The Jail is the 5th largest in the United States and houses between 4,000 and 4,500 inmates. The microgrid provides critical power to the Jail when the site loses utility power. The microgrid is designed using multiple generation sources including: diesel generators, a combined heat and power gas driven fuel cell, electrochemical energy storage, small wind and various types of both fixed and tracking photovoltaic systems. Even when the jail is connected to the utility, the microgrid assets provide much of the power to serve the site's electrical loads without back-feeding power to the utility. The object of this report is to provide the monitoring and verification results for the 1st year including an assessment of hardware and software capabilities to monitor, collect data, and control the microgrid system. The first task, 23.1-A, provides an assessment that informed system designers about any limitations or issues with the installed system and provides an outline some best practices of how to achieve robust and optimal microgrid system control, and provides recommendations for future installations and/or upgrades. The second task, 23.1-B, provides the results of a system level evaluation through simulation of the microgrid using the Homer modeling tool to provide further insight in the cost savings for various scenarios.

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Introduction

The objective of the overall microgrid project is to design, deploy and optimize the performance of an advanced microgrid that includes a photovoltaic (PV) solar array, a fuel cell, a battery and diesel fueled engine generators at the Alameda County Santa Rita Jail located in Dublin, California. The primary purpose of the microgrid is to provide backup power to critical electrical loads at the facility if there is a loss of power from the electric utility. Under normal conditions, when the microgrid is electrically connected to the utility, power generated by the solar array, fuel cell and battery are operated together with electrical power from the utility to provide power to the jail facility. The system monitors the status of the utility and provides a seamless transfer between grid-connected and islanded operation in cases of when utility outages or power quality issues occur. Alameda County, California Public Utilities Commission, Pacific Gas and Electric, the U.S. Department of Energy, the Department of Defense Climate Change Fuel Cell Program, the California Energy Commission, the California Public Utilities Commission, and California Self-generating Incentive Program provide funding for the microgrid project.

Under funding provided by the U.S. Department of Energy (DOE), The National Renewable Energy Laboratory (NREL) provides technical support to the project to monitor and validate the performance of the microgrid's sensors, components, systems, and controls, and suggest recommendations for operational and equipment improvements through site visits, analysis and simulation.

The overall layout for the Santa Rita Jail Microgrid is given in Figure 1. The facility includes: Two 1.2 MW engine-driven generators that are fueled using diesel; roof-mounted solar arrays at the housing units; tracking solar arrays, a natural gas-fueled, molten carbonate fuel cell fueled by natural gas; four 500 kW lithium ion battery storage systems; and five small wind turbines. Each of the generating sources is connected at different points on the campus electrical distribution system.

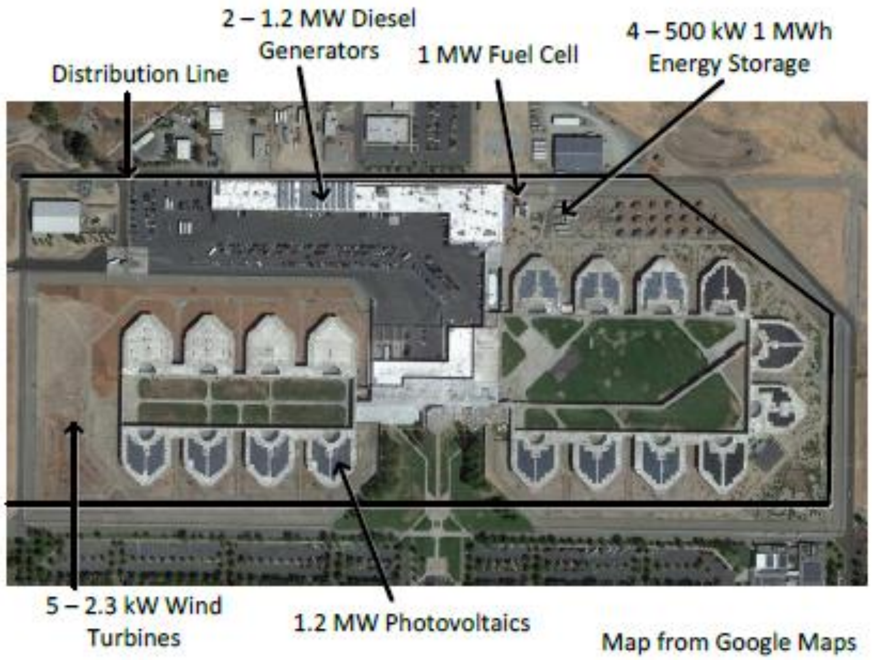

Figure 1 Santa Rita Jail Microgrid Layout

Prior to the deployment of the microgrid, the two 1.2 MW diesel generators were the only sources of power for backup power. The addition of the new microgrid generation resources provides redundancy in power generation, reduced diesel usage during emergency microgrid operation, and a reduction in the power provided by the utility during grid-connected operation. The jail uses automated systems that deliver laundry, supplies, and food to the campus. It also includes on-site medical and mental health services. Continuous electric power delivery is essential for the facility's operation.

The primary reason the microgrid was installed is to provide backup power to critical electrical loads at the jail should there be a loss of power. Under normal conditions, when the microgrid is electrically connected to the utility, power generated by the solar array, fuel cell and battery are operated together to reduce the power required from PG&E. The fuel cell operates with an efficiency of approximately 47%. The energy storage control design is intended reduces load during the peak period from noon to 6 pm and also prevents power export. The energy storage is designed to charge during the night. Table 1 below provides the rated capacity for the on-site generation systems installed at the campus.

Table 1 Santa Rita Jail Microgrid Generation Resources

Rated Power	Generator Type
1.2 MW	Solar PV array
1 MW	Fuel cell with heat recovery for domestic hot water, molten carbonate technology
2.4 MW	Diesel Generators
2 MW	Lithium ion energy storage, 4 MWh capacity (3 MWh useable)
11.5 kW	5 Wind Turbines
6.61 MW	**Total generation**

The Santa Rita Jail uses a loop distribution system as shown on Figure 2. The electrical distribution circuit is designed to provide both reliability and flexibility for electricity delivery. If a device fails, such as a transformer within the Santa Rita Jail distribution system, the device can be isolated from the distribution circuit using switches to allow remaining systems to operate. The distribution circuit is designed so that the electrical loads can be fed from two different electric busses.

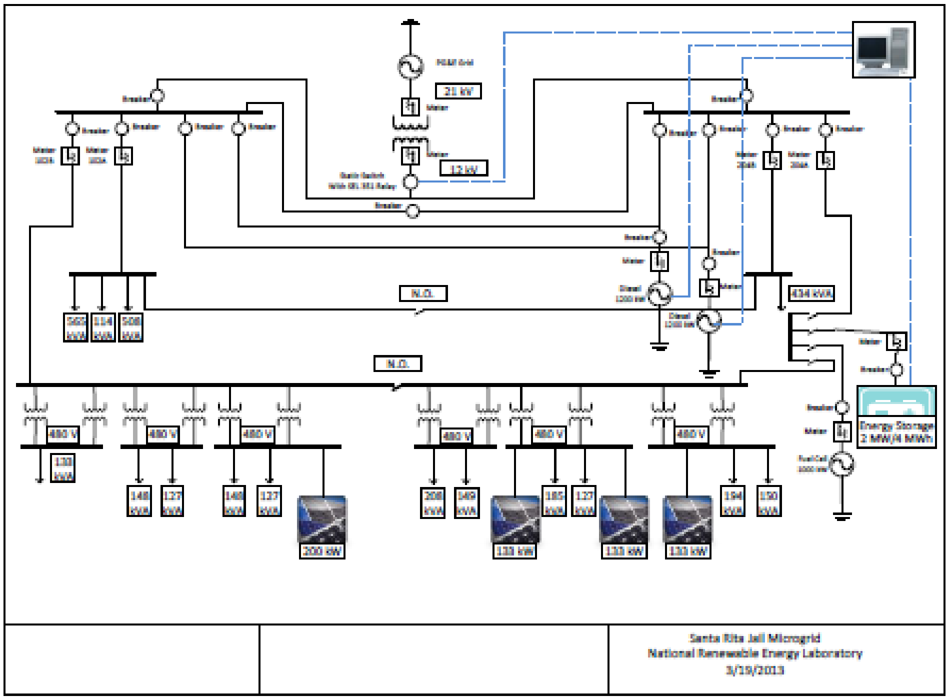

Figure 2 Santa Rita Jail Electric Distribution System

If a utility outage occurs, the Santa Rita Jail microgrid is designed to disconnect from the utility feed using the static switch at the 12 kV service entries shown at the top of Figure 2. The static switch is a fast acting switch that can switch much faster than a conventional circuit breaker. Once isolated from the utility, the design intent is to immediately utilize the microgrid generation assets to provide the power required to serve the facility's loads. The system is designed using the Consortium for Electric Reliability Technology Solutions, CERTS, control methodology. CERTS provide a seamless transition back and forth between utility-connected and islanded conditions. The advantage of this control methodology in that it allows the entire microgrid generating resources to always operate in voltage mode control, even when connected to the utility.

This report provides the results for Subtask 23.1-A and 23.1-B listed in the Chevron statement of work to Alameda County. The report is separated into six sections and includes an Executive Summary, Bibliography, and List of Acronyms. Section 1 of the report provides an evaluation of the monitoring, metering and data acquisition systems. Section 2 of this report describes the simulation results for sizing energy storage needed for different fuel cell and PV output power using the simulation tool Homer. The section also estimates monthly demand and energy savings and other financial opportunities for cost saving

1 Task 23.1-A Evaluation of Monitoring, Metering and Data Acquisition Systems

1.1 Metering

The metering at the site includes two main power meters: the ION 6200 and the ION 7650. Each meter is currently set to measure power and energy variables in 15-minute intervals. The power meters have the capability for more frequent measurements through a program interface including event triggering. The type of measurement and communications available for the two power meters are given in Table 2 and Table 3.

Table 2 ION 6200 Power Meter

Measurements	Communications
Voltage L-N	Modbus
Voltage L-L	RS-485
Frequency	
Current	
kW	
kWh	
pf	
Voltage THD	
Current THD	

Table 3 ION 7650 Power Meter

Measurements	Communications
Power, energy, demand	IEC 61850
Harmonics	RS-232/485; Ethernet; optical
Symmetrical components: zero, positive, negative	Internal Modem
Flicker	DNP 3.0
Time Stamp	Modbus; Modbus TCP

	EtherGater, Modem Gate, MeterM@il, WebMeter
	Relay outputs

1.2 Network and Servers

The communication network for the microgrid contains components from both Encorp and Applied Power Technologies, Inc. (APT). Encorp installed "Gold Boxes" which are programmable logic controllers (PLC) for the static switch, the diesel generators, the energy storage, and the load control. It provides the hardware interface between many power devices including meters, relays, human machine interface, servers, and other equipment. APT provided the power meters and programmed the PLC for control of the energy storage. APT provided a server that acts as a supervisory controller and stores power data from the microgrid meters and can display power data in real time.

1.3 Load Control Summary

The Encorp control system includes a method for load shedding. The loads are classified into three categories: 'A', 'B', and 'C'. 'A' loads are the most critical loads; 'B' loads are the next most critical loads, and 'C' loads are the least critical loads. The human machine interface allows the controllable loads to be programmed into any category at anytime. The microgrid control defines which loads will be connected under various conditions. For example, during grid-connected, non-islanded operations all of jails loads are connected. Should power from the utility be lost and the microgrid disconnects from the utility, 'C' loads are shut off while 'A' and 'B' loads remain connected to the microgrid sources. If the frequency falls out of a set frequency range, the 'B' loads will be disconnected.

1.4 Recommendations for Metering and Monitoring

- Develop procedures and companion software for the operations staff to follow should in case of the failure of the communications or supervisory control.
- Perform regular security audits and maintain software revision control as the system undergoes software and hardware upgrades.
- Provide a redundant server that can take control in real-time should the primary server fails.
- Calibrate meters and sensors on a six or twelve month cycle.
- Add a weather station including solar irradiance sensing and full sky imagery.
- Instrument or provide a means to collect data on un-monitored PV systems at the site together with the other microgrid data.

2 Task 23.1-B System Modeling and Analysis

2.1 Homer Simulation Tool

The HOMER simulation tool can be used to estimate the best equipment sizes for optimizing the economics, and overall dispatch operation of a microgrid. The model uses cost and simulated power output predictions for the optimization. The HOMER calculations used in this report were made based on an hour time step. HOMER does not calculate voltages and currents or simulate grid transients in the sub-millisecond time. A simulation study was conducted to estimate necessary energy storage sizes for each recommendation. The primary inputs used for the simulation are given in Table 4.

Table 4 HOMER Simulation Inputs and Outputs

Inputs	Outputs
Wind resources Solar resource Electric costs from PG&E Schedule E-20 (Table 6) Diesel operation Natural gas costs for fuel cell Wind operation and maintenance costs Solar operation and maintenance costs Fuel cell operation and maintenance costs Energy storage operation and maintenance Costs	Operation of loads and generation

HOMER uses yearly profiles for each source. At the time the simulation was conducted, only two days of data for site were available. The Homer simulation utilized a scaled yearly load profile that PG&E's publishes on their website to describe the average dynamic load profiles for each of its rate customers. The average customer load profile was scaled to match the Jail's measured loads for July 17, 2012 and July 18, 2012 as shown in Figure 3. The solar production profile for the site was approximated using yearly solar irradiance data for the site from a software tool called PVWatts developed at NREL. PVWatts approximates solar output of a theoretical PV array based on past irradiance data for sites across the world. An Irradiance meter located close to Dublin, CA was used to estimate the yearly irradiance data. The PV solar system size was adjusted to match the solar output from the data in Figure 3. As a result, the modeled PV system was a single 550 kW PV system which represents where the amount of PV power the site is currently producing which is much less that the rated power.

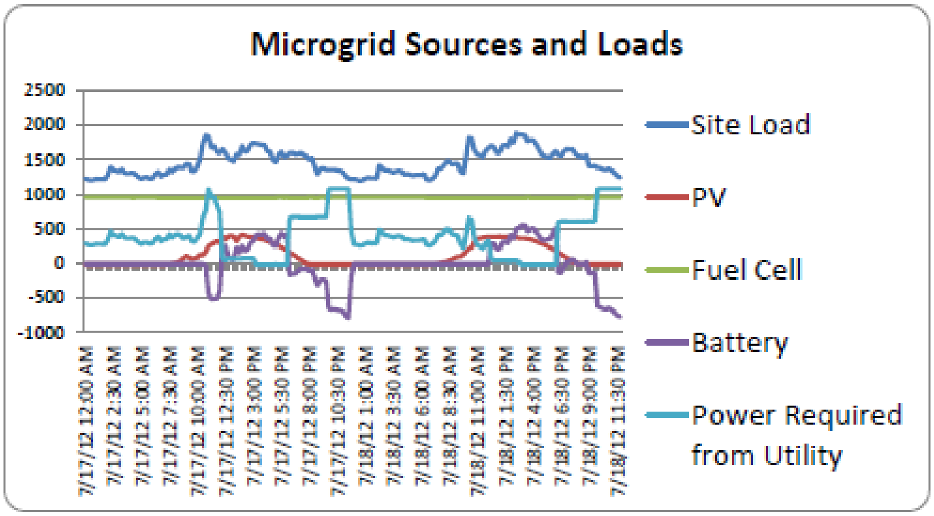

Figure 3 Site Load and Microgrid Energy Sources

The HOMER simulation was setup to predict the minimum required energy storage power and energy storage capacity necessary for preventing export to the utility using the existing PV and Fuel Cell generating sources as well as due to increasing the fuel cell and solar PV power production. The analysis assumed that the PV and fuel cell power could not be modulated or controlled to match the estimated scaled electrical site load described above. Homer simulations were conducted and analyzed for one year. Figure 4 through Figure 7 show the results to determine the days that would have the greatest impact on the energy storage requirments given the generation scenario that was simulated avoid power export to the utility and is depicted as the "Excess Electricity" curve in each of the Figures. The required energy required by the battery was estimated by integrating the area under the "Excess Electricity" curve. The plot labeled "AC Primary Load" is the approximate load of the site using the two days of data used for the model and scaled site load based on PG&E's published load profiles. The plot labeled "PV Power" is the approximate PV electric power output. The plot labeled "Fuel Cell Power" is the electrical power output of the fuel cell.

Table 5 provides a summary of the simulation results to estimate the energy storage requirements should the jail consider adding additional PV and fuel cell generation resources.

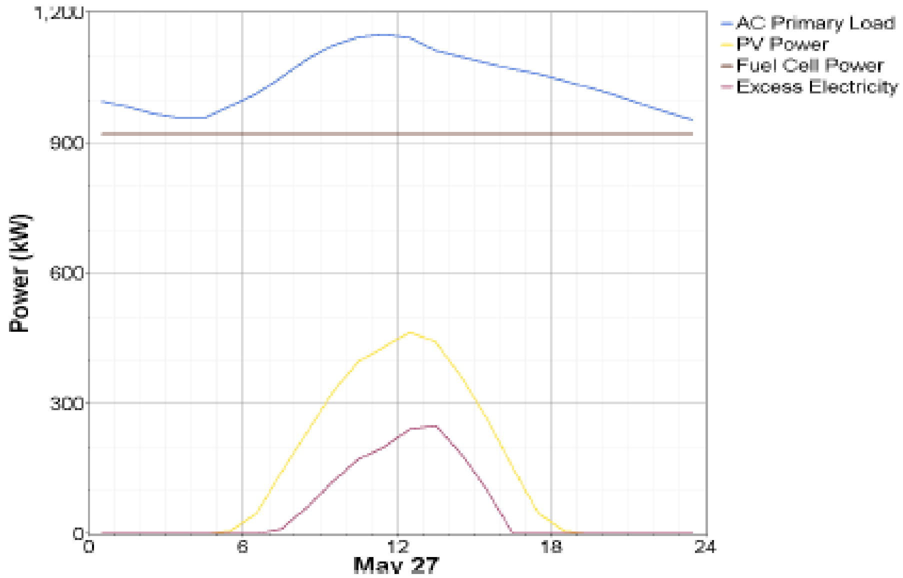

Figure 4 HOMER Simulations for Baseline PV and Fuel Cell

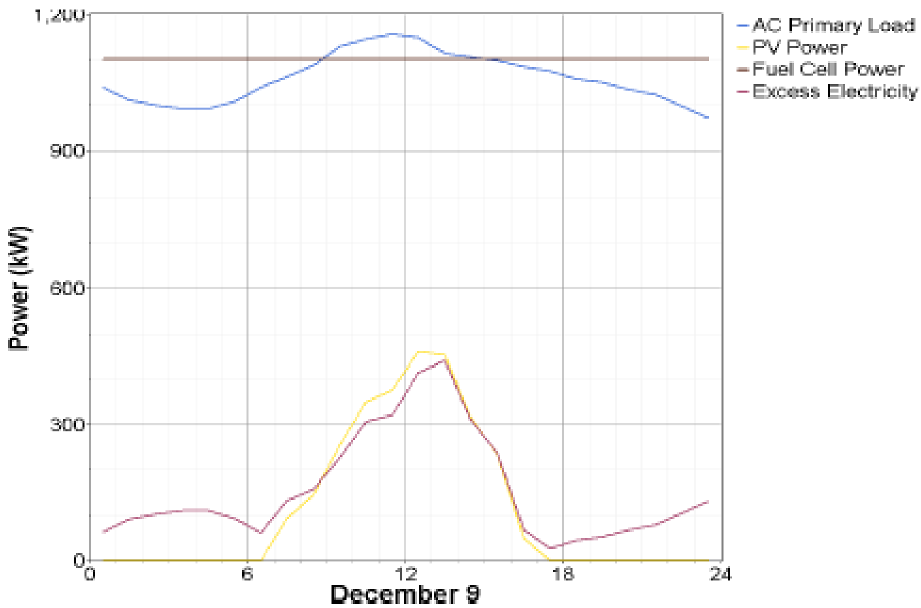

Figure 5 HOMER Simulations for 1,100 kW Fuel Cell and Baseline PV

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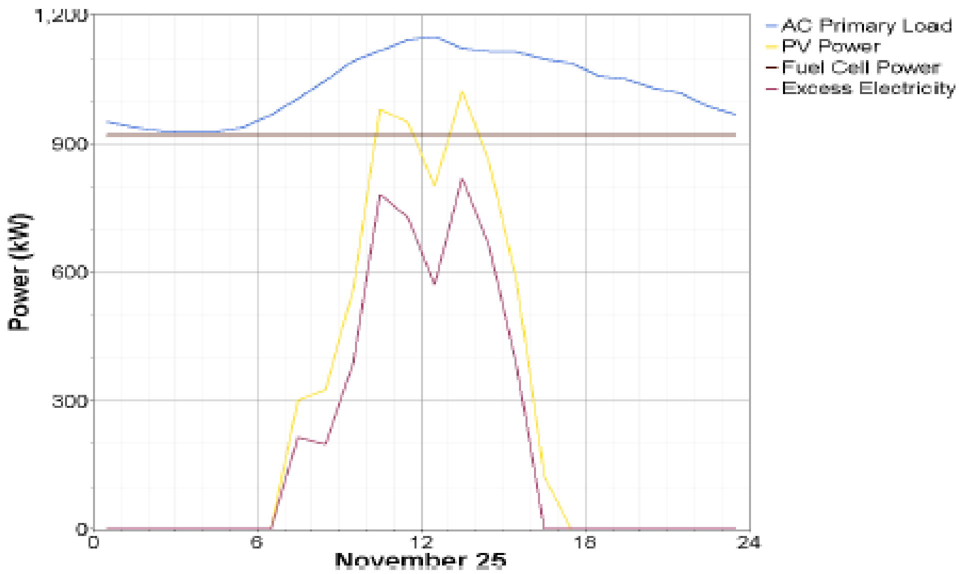

Figure 6 HOMER Simulations for Baseline Fuel Cell and 1,200 kW PV

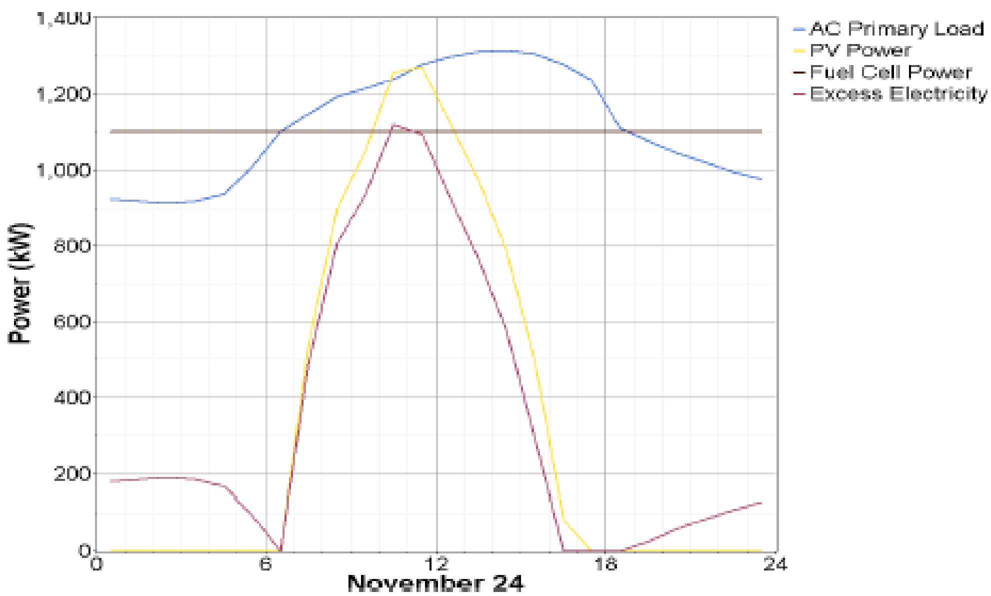

Figure 7 HOMER Simulations for 1,100 kW Fuel Cell and 1,200 kW PV

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Table 5 Estimated Energy Storage as a Function of Fuel Cell and PV Size

Fuel Cell Size	PV Operation	Required Energy Storage	Figure Reference
950 kW	550kW (existing)	500 kW, 3 MWh (existing)	(Figure 4)
1100 kW	550 kW (existing)	1 MW, 5 MWh	(Figure 5)
950 kW	1.2 MW output	2 MW, over 5 MWh	(Figure 6)
1100 kW	1.2 MW output	2 MW, 10 MWh	(Figure 7)

It should again be noted that actual loads for a year were not available at the time the Homer simulation was conducted. The control strategy implemented at the time of this report charges the battery during the off-peak hours with the goal of being at full SOC in order to reduce peak electric demand. Future dynamic simulations could be conducted using actual yearly load data to evaluate existing and future generation resource scenarios and control methodologies.

2.2 Santa Rita Load Analysis

Alameda County provided operational data for microgrid operations to NREL for one year beginning in January 2012. Analysis of the data for the year showed that the minimum demand occurred between January 14, 2012 and January 21, 2013. Figure 8 shows a plot of the demand during this time period. Analysis of the data shows that site exported 4.8 kW back to the utility for a few of the 15-min demand time intervals during this time period.

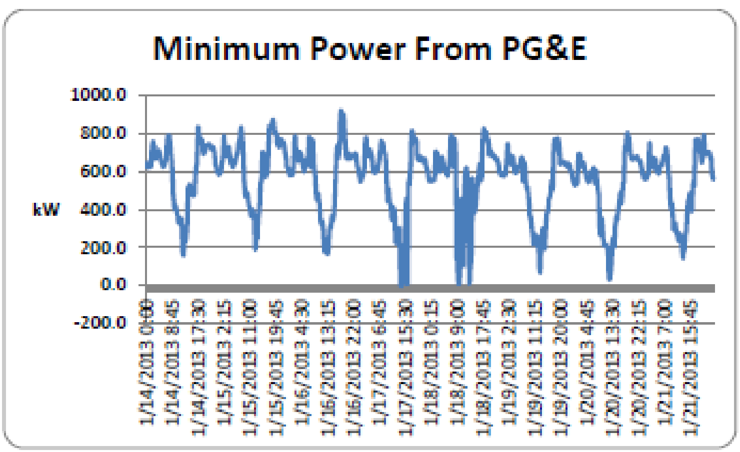

Figure 8 Minimum Power Demand Provided from PG&E 1/14 to 1/21

Figure 9 shows that the maximum demand provided by the utility for the site occurred between November 25, 2012 and December 1, 2012. The data shows that the power spiked to about 2,300 kW. The average demand during the first part of the week was 500kW and the average demand at the end of the week was about 1,500 kW.

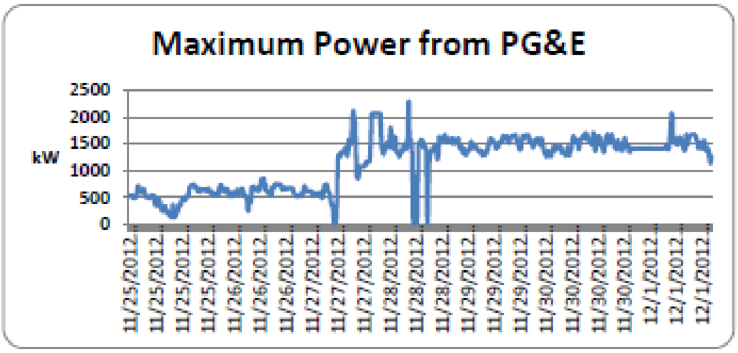

Figure 9 Maximum Power Demand Provided from PG&E 11/25 to 12/1

The total site demand is a measurement of the total power required to serve the site's load that is provided by both the utility and the microgrid generation assets. Analysis of the data for a year shows that the minimum total demand occurred between November 25, 2012 and December 1, 2012. A graph for the total demand during this time period is given in Figure 10. The outages shown in the Figure represent the expected outages that occurred during commissioning.

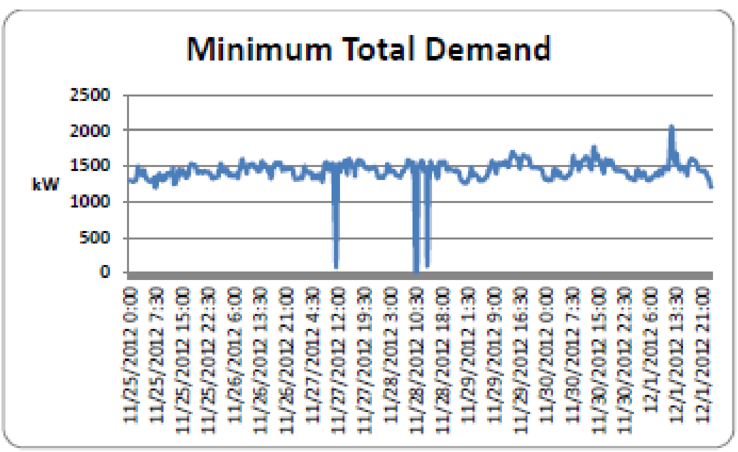

Figure 10 Minimum Total Site Power Demand 11/25 to 12/1

Table 6 PG&E Electricity Rate Schedule E-20 Primary

Rate Name	Times	Days	Rate ($)
Maximum Peak Demand Summer ($/kW)	12:00 noon to 6:00 p.m.	Monday-Friday except holidays	$15.40/kW
Maximum Part-Peak Demand Summer ($/kW)	8:30 a.m. to 12:00 noon and 6:00 p.m. to 9:30 p.m.	Monday-Friday except holidays	$3.23/kW
Maximum Demand Summer ($/kW)			$9.33/kW
Maximum Part-Peak Demand Winter	8:30 a.m. to 9:30 p.m.	Monday-Friday except holidays	$0.25/kW
Maximum Demand Winter ($/kW)			$9.33/kW
Peak Summer ($/kWh)	12:00 noon to 6:00 p.m.	Monday-Friday except holidays	$0.13097/kWh
Part Peak Summer ($/kWh)	8:30 a.m. to 12:00 noon and 6:00 p.m. to 9:30 p.m.	Monday-Friday except holidays	$0.09268/kWh
Off-Peak Summer ($/kWh)	9:30pm to 8:30 a.m. and All day on weekends/holidays		$0.07028/kWh
Part-Peak Winter ($/kWh)	8:30 a.m. to 9:30 p.m.	Monday-Friday except holidays	$0.08835/kWh
Off-Peak Winter ($/kWh)	9:30 p.m. to 8:30 a.m. and all day on weekends/holidays		$0.07376/kWh

Note: pf Adjustment rate ($/kWh/%): $0.00005/kWh/%

Note: Summer (May 1 to October 31), winter (November 1 to April 30)

Additionally, the pf charge is $0.00005/kWh/%. The rate states:

> The rate charges (based on actual utility bill for the site) are adjusted based upon the power factor. The power factor is computed from the ratio of lagging reactive kilovolt-ampere-hours to the kilowatt-hours consumed in the month. Power factors are rounded to the nearest whole percent. The rates in this schedule are based on a power factor of 85 percent. If the average power factor is greater than 85 percent, the total monthly bill will be reduced by the product of the power factor rate and the kilowatt-hour usage for each percentage point above 85 percent. If the average power factor is below 85 percent, the total monthly

bill will be increased by the product of the power factor rate and the kilowatt-hour usage for each percentage point below 85 percent. Power factor adjustments will be assigned to distribution for billing purposes.

For example, if the meter used for billing at the point of common coupling (PCC) measures a pf of 0.7 and a power level of 300 kW for one hour then the rate will be (1):

$$pF_{rate} = 0.00005 \times (0.85 - 0.7) \times 100 \times 300kW \times 1_{hour} = \$0.225 \tag{1}$$

Table 7 provides the costs/therm rates for each month during 2012 for the site.

Table 7 Santa Rita Jail Monthly Natural Gas Rates

Month	Natural Gas Rate
January 2012	$0.469/Therm
February 2012	$0.459/Therm
March 2012	$0.44/Therm
April 2012	$0.417/Therm
May 2012	$0.431/Therm
June 2012	$0.476/Therm
July 2012	$0.46/Therm
August 2012	$0.48/Therm
September 2012	$0.459/Therm
October 2012	$0.477/Therm
November 2012	$0.494/Therm
December 2012	$0.493/Therm

When the microgrid is grid-connected the amount of power and energy required by the Jail from the utility the microgrid generation resources assist the utility resources to serve the Jail's electrical load. Figure 12 provides an estimate of the monthly electrical demand savings and Figure 13 provides an estimate of the electric energy reduction required from the utility. Both measurements are measured at the point of common coupling between the Utility and Jail's microgrid. Figure 12 shows that during July 2012, 3 different demand rates must be considered for to determine demand including: the maximum peak demand, part-peak demand, and the maximum demand. The part-peak summer period shown in red occurs from 8:30 a.m. to noon and 6:00 p.m. to 9:30 p.m. The reduced demand is primarily due to the fuel cell and PV power generation. If the microgrid generation was not operating properly for only one-15 minute interval during the month, Alameda County would have been assessed an estimated demand charge of 825 kW at a rate over $15/kW.

The maximum total demand occurred during the week of March 23rd to March 30th in 2013 and is given in Figure 11. The maximum total demand used by site's loads was over 3,000 kW during this week.

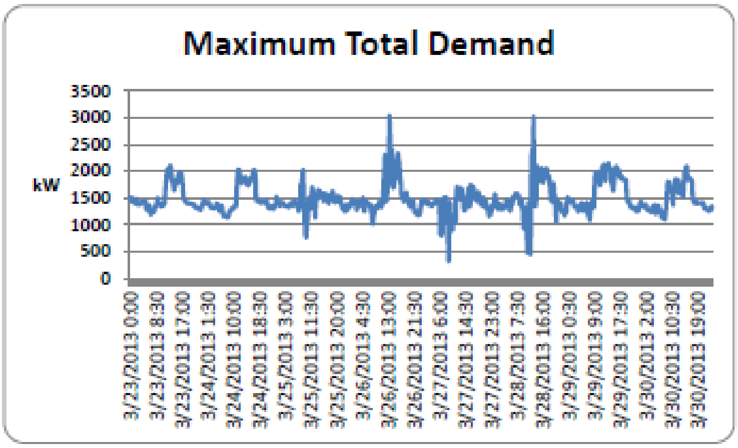

Figure 11 Maximum Total Site Power Demand Used 3/23 to 3/30

2.3 Microgrid Cost Savings During Grid-Connected Operations

Further analysis was performed to estimate the monthly electrical energy and demand savings that the microgrid generation assets provide during grid-connected operations. When the microgrid is grid-connected to the utility the amount of power and energy required by the Jail from the utility is reduced as the microgrid generation resources assist the utility resources to serve the Jail's electrical loads. Table 6 gives a summary of costs that PG&E's charges during various time and season intervals. The data for the table is based on The E-20 rate structure from PG&E's web site. The table shows that he highest utility costs for both demand and energy occur between 12AM and 6PM Monday through Friday during the summer where the peak demand charge is $15.40/W and the peak energy charge $0.13097/kWh.

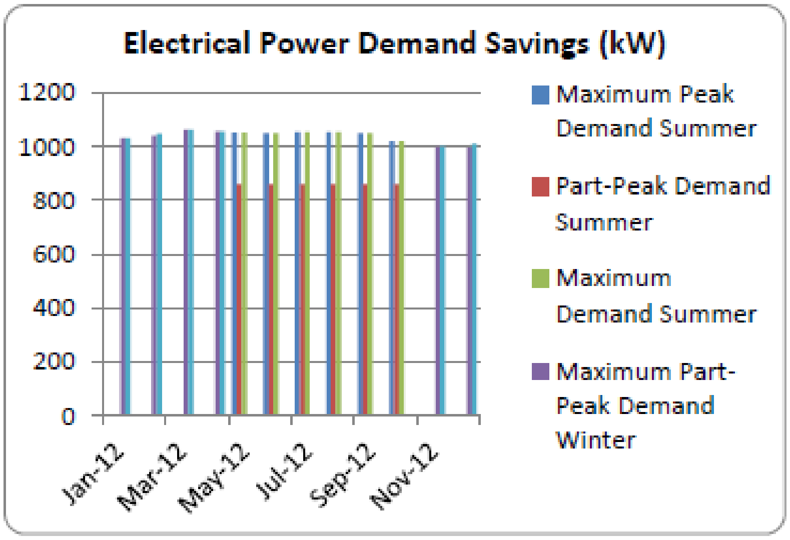

Figure 12 Estimated Monthly Demand Savings (kW)

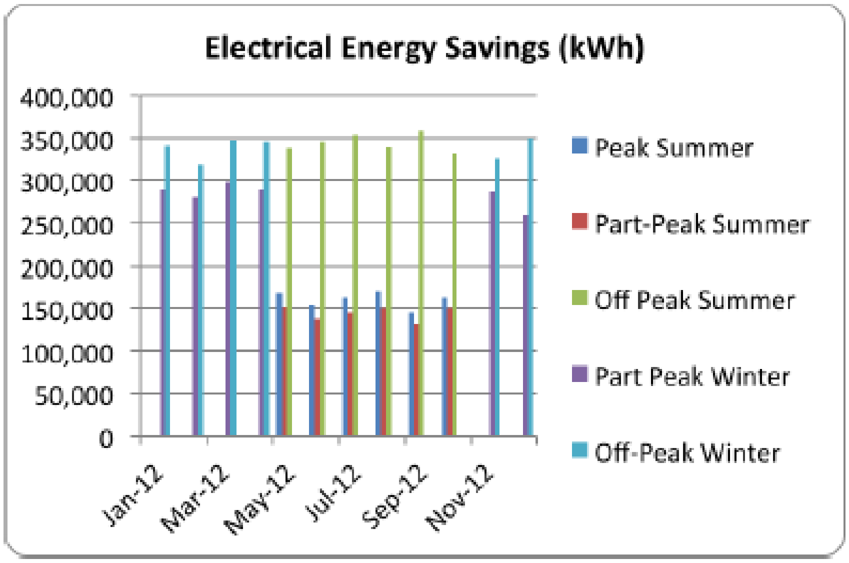

Figure 13 Estimated Monthly Energy Savings (kWh)

24

Using the data from Figure 12, Figure 13 and the rate tables above, the estimate dollar cost savings for both demand and energy are given in Figure 14 and Figure 15 respectfully.

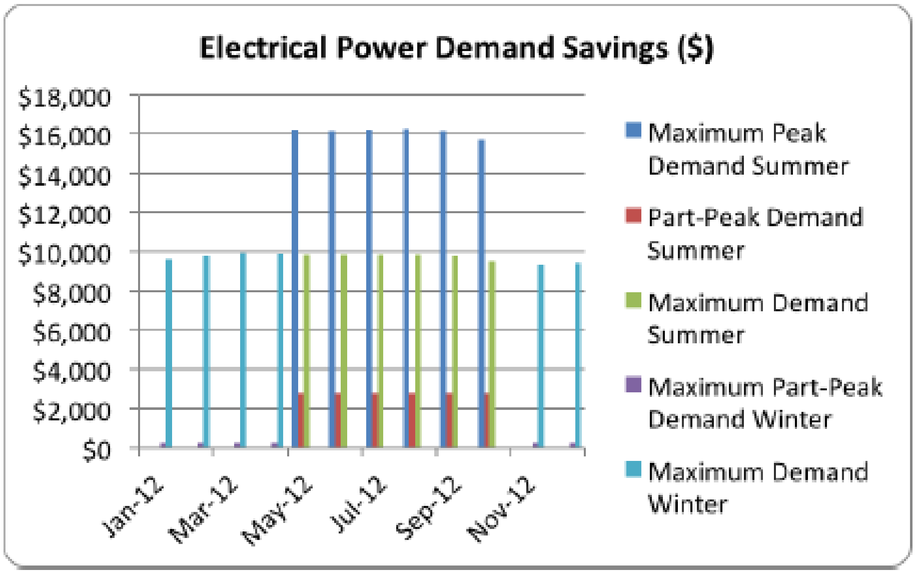

Figure 14 Estimated Monthly Demand Savings ($)

25

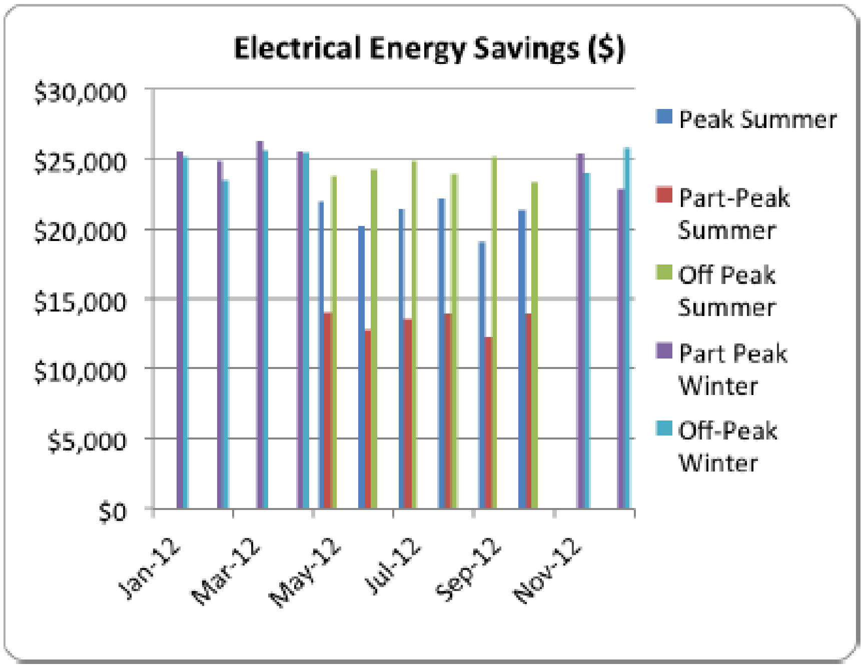

Figure 15 Estimated Monthly Energy Cost Savings ($)

The predicted total utility cost savings for each month is the sum of the demand and energy cost savings.

2.4 Recommendations

- An advanced control strategy to control both the generation sources and loads together should be considered that can more effectively reduce the summer electric demand and to allow Alameda county to effectively participated in PG&E's demand response programs. Table 8 provides a description of each demand programs from PG&E's website for Alameda County to consider together with PG&E.

- Hardware and software control systems should be designed to keep the system running 24/7 to avoid peak demand and energy charges from the utility.

Table 8 PG&E Demand Response Programs 2013

Program	Incentive	Requirement	
Peak Day Pricing (PDP)	**Reduced Rates**	Customers who participate in PDP will experience between 9 and 15 PDP Event Days annually in addition to time-of-use pricing. On PDP Event Days, a surcharge is added to a portion of the peak period (i.e., from 2 p.m. to 6 p.m.) which customers will pay in addition to their regular peak electric rate.	http://www.pge.com/mybusiness/energysavingsrebates/timevaryingpricing/peakdaypricing/
Base Interruptible Program (BIP)	**$9/kW**	BIP gives you 30 minutes advance notice. You will receive a monthly incentive payment even if no events are called. However, failure to reduce load down to or below your Firm Service Level during an event will result in a charge of $6.00/kWh for any energy use above the Firm Service Level. There is a maximum of one event per day and four hours per event. The Program will not exceed 10 events per month, or 120 hours per year.	http://www.pge.com/mybusiness/energysavingsrebates/demandresponse/baseinterruptible/
Demand Bidding Program (DBP)	**$0.50/kW or $0.60/kW**	For day-ahead events, you will receive an event notice by noon on the business day before the planned event. You will have until 3 p.m. that day to submit bids via InterAct. For day-of events, you will have one hour after receiving the event notice to submit bids via InterAct. PG&E will notify participants of bid acceptance within 15 minutes of the bid acceptance window closing.	http://www.pge.com/mybusiness/energysavingsrebates/demandresponse/dbp/
Optional Binding Mandatory Curtailment (OBMC) Plan	**Varies**		http://www.pge.com/mybusiness/energysavingsrebates/demandresponse/obmcp/
Scheduled Load Reduction Program (SLRP)		You select one to three four-hour time periods (between 8 a.m. and 8 p.m.) on one or more weekdays. You are required to reduce load each and every time your selected SLRP options (day of the week and corresponding elected time) occur. Your load reduction cannot be shifted to an on-peak time period (noon to 6 p.m.) on another day.	http://www.pge.com/mybusiness/energysavingsrebates/demandresponse/slrp/
Permanent Load Shift	**Under Development**		
SmartAC	**No Longer Available**		
Aggregator Managed Portfolio (AMP)	**Varies**	Many aggregators possible	http://www.pge.com/mybusiness/energysavingsrebates/demandresponse/amp/

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Capacity Bidding Program (CBP)	**Varies**	Load reduction commitment is on a month-by-month basis, with nominations made five days prior to the beginning of each month. Customers must enroll with (or as) a third-party aggregator to join the Capacity Bidding Program. 1-4 Hour: June: $4.27/kW. July: $17.94/kW. August: $24.81/kW. September: $15.30/kW.	http://www.pge.com/mybusiness/energysavingsrebates/demandresponse/cbp/
Automated Demand Response	**Between $125/kW and $400/kW**	PG&E pays between $125 per kilowatt (kW) and $400 per kW of DR load reduction (dispatchable load) that will be controlled by the technology, depending upon the technology category program selected.	http://www.pge.com/mybusiness/energysavingsrebates/demandresponse/adrp/
Dual Enrollment	**Many options**	Varies options with PDP, BIP, DBP, OBMC, AMP, CBP	http://www.pge.com/includes/docs/pdfs/mybusiness/energysavingsrebates/demandresponse/baseinterruptable/DR_DualParticipation.pdf

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Santa Rita Jail Microgrid Report

Annabelle Pratt (based on work by W. Kramer, D. Martin, G. Martin)
National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report for Subtasks 23.1-A and 23.1-B
Santa Rita Jail Project
April 2014

Contract No. DE-AC36-08GO28308

NATIONAL RENEWABLE ENERGY LABORATORY

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Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 1

Acknowledgements

The authors would like to thank the U.S. Department of Energy, Alameda County, Chevron Energy Solutions, Lawrence Berkeley National Laboratory and the following people for their support: Merrill Smith, Matthew Muniz, Eduardo Alegria, Osama Idrees, Anthony Ma, Craig Gee, Furqan Saleemi, Erin Minear, Chris Marnay, Sam Sprik, Chris Ainscough, , and Ben Kroposki.

List of Acronyms

CERTS	Consortium for Electric Reliability Technology Solutions
DOE	U.S. Department of Energy
HOMER	Hybrid Optimization Model for Electric Renewables
NREL	National Renewable Energy Laboratory
PCC	Point of common coupling
PF	Power factor
PG&E	Pacific Gas and Electric Company
PV	Photovoltaic
VAR	Volt Ampere Reactive

Executive Summary

The Santa Rita Jail is located in Dublin, California within Alameda County. The jail is the fifth largest in the United States and houses between 4,000 and 4,500 inmates. The facility's electric load varies between 1.5 MW and 2 MW, with the higher loads occurring in summer due to air-conditioning. An on-site microgrid provides critical power to the jail when utility power is lost. When the jail is connected to the utility, the microgrid equipment provides much of the power to serve the site's electrical loads without exporting power to the utility.

The microgrid is composed of multiple distributed energy resources, installed over a number of years, including diesel generators, a combined heat and power gas-driven fuel cell, electrochemical (battery) energy storage, small wind turbines and various types of both fixed and tracking photovoltaic systems.

The object of the current project was to model the microgrid and estimate potential cost savings, and then to analyze data over a two year period of operation of the microgrid, in order to calculate actual cost savings and compare to potential cost savings, and suggest potential operational strategies to further reduce energy costs at the jail.

NREL used HOMER software to simulate the microgrid operations for one year. The PVWatts tool was used to generate solar resource data for the year based on data from a weather station close to Dublin. Due to initial limitations on data availability, this model was created using load data covering only a two day period, yet the estimated potential savings match the calculated savings based on measured data fairly well. With the HOMER model, we were also able to investigate energy storage requirements for increases in fuel cell and/or photovoltaic (PV) system capacities.

Two years' worth of natural gas and power data was analyzed to calculate utility energy and demand reductions, and corresponding cost savings. The distributed energy resources provided 60% of the energy required by the facility in 2012 and 49% of the energy required in 2013. Total cost savings attributable to the microgrid were $447,000 in 2012 and $378,000 in 2013.

Things to note:

- The system frequently uses the battery system, along with the other microgrid sources, to reduce the utility power to zero. Battery system control under these circumstances is critical to prevent exporting power back to the grid.
- The batteries are sometimes charged at such a high rate that this effectively sets the peak demand for the month. Charging at a lower rate should be investigated.
- In 2013 (and part of 2012), the fuel cell was frequently operated below its rated output, decreasing potential electric demand and energy savings.
- The chillers could be used as part of the load control strategy to reduce total utility costs
- It might be possible to use the diesel generators as part of the load control strategy to reduce total utility costs (if operating permits allow)
- The fuel cell is also used to heat domestic water. Cost and energy savings attributable to this are not accounted for in this analysis.

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1 Introduction

This report summarizes the results of two subtasks listed in the Chevron statement of work with Alameda County—Subtask 23.1-A and 23.1-B.

This section provides background information for the remainder of the report, including the history of the microgrid and the distributed generation components that provide power and energy storage for the Santa Rita Jail.

1.1 Santa Rita Jail Microgrid History

In 2011, to demonstrate successful integration of renewable distributed generation, advanced energy storage and demand response initiatives, Chevron installed a microgrid at the Santa Rita Jail. This addition was intended to optimize the benefits of existing generation and storage assets at the site, by reliably shaving peak demand. The microgrid project included the installation of a 2-MW battery system—which has a 4-MWh capacity rating—a static transfer switch, and a generation monitoring and control system. Combined with already-existing components, like a fuel cell, wind turbines and PV modules, this battery extended the capability of following the jail's electrical load, and was originally envisioned to provide sufficient generation capacity to meet approximately eight hours of the jail's full power needs.

Alameda County, California Public Utilities Commission, Pacific Gas and Electric, the U.S. Department of Energy, the Department of Defense Climate Change Fuel Cell Program, the California Energy Commission, the California Public Utilities Commission, and California Self-generating Incentive Program provide funding for the microgrid project.

1.2 NREL's Role

NREL worked with Chevron and the Santa Rita Jail to model the current microgrid distributed resources and identify enhancements that can improve the microgrid operation. We also monitored and analyzed operational data for the microgrid. This report provides a summary of the modeling and analysis.

NREL deliverables include the following:

- Review of monitoring and metering equipment, data acquisition, and data logging and management plan.
- Results of HOMER system model analysis
- Report on overall analysis

1.3 Santa Rita Jail Microgrid—Technical Details

The Santa Rita Jail is located in Dublin, California within Alameda County. The jail is the fifth largest in the United States and houses between 4,000 and 4,500 inmates. The jail uses automated systems that deliver laundry, supplies, and food to the campus. It also includes on-site medical and mental health services. Continuous electric power delivery is essential for the facility's operation. Prior to the deployment of the microgrid, two 1.2 MW diesel generators were the only sources of backup power.

Over a period of a decade, distributed energy systems were installed, including 1.2 MW of rooftop PV in 2002. A battery system installed in 2011 allowed all of the distributed energy resources to form a microgrid. These generation sources provide redundancy in power generation, reduce diesel usage during emergency microgrid operation, and reduce power purchased from the utility during grid-connected operation. But the primary purpose of the microgrid is to provide backup power to critical electrical loads at the jail should there be a loss of utility power.

The storage and generation assets installed on the jail campus are summarized in Table 1, and include the following: two 1.2 MW diesel generators, roof-mounted solar arrays, tracking solar arrays, a natural gas-fueled molten carbonate fuel cell[1], five small wind turbines, and four 500 kW, 1-MWh, lithium ion battery storage systems. The components are connected at different points on the campus electrical distribution system.

Table 1: Santa Rita Jail microgrid generation resources

Generator Type	Rated Power
Solar PV arrays	1.2 MW
Fuel cell with heat recovery for domestic hot water, molten carbonate technology	1.0 MW
Diesel Generators	2.4 MW
Lithium ion battery storage, 4 MWh capacity (3 MWh useable)	2.0 MW
5 Wind Turbines	11.5 kW
Total generation	**6.61 MW**

Under normal conditions, when the microgrid is electrically connected to the utility, power generated by the wind turbines, solar arrays, fuel cell and batteries are operated together to reduce the power and energy purchased from PG&E. The energy control system prevents power export to—and is intended to reduce peak demand from—the utility during times when those costs are highest. It is designed to charge the batteries at night, when costs are lowest. The overall layout for the Santa Rita Jail microgrid is shown in Figure 1.

[1] The fuel cell also provides about 15% of the hot water demand at the jail, and operates with an electrical efficiency of approximately 47%.

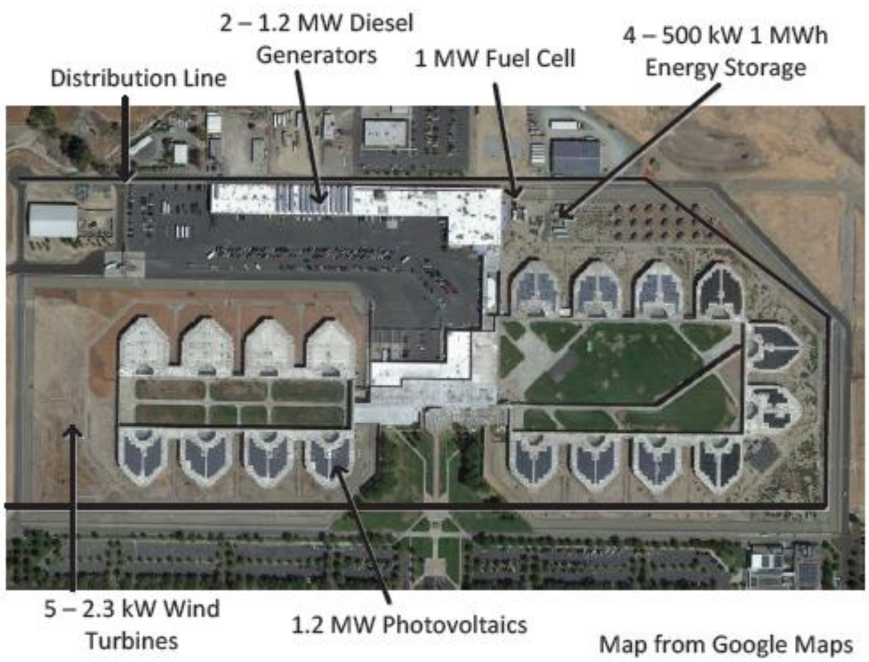

Figure 1: Santa Rita Jail microgrid layout

The microgrid is designed to disconnect from the utility in the event of a utility outage, using the static switch—a fast-acting switch that is much faster than a conventional circuit breaker—at the 12 kV service entrance shown at the top of Figure 2, and to immediately use the microgrid generation assets to provide the power required to serve the facility's critical loads.

The system is designed using the Consortium for Electric Reliability Technology Solutions (CERTS) control methodology, which provides a seamless transition back and forth between utility-connected and islanded conditions, flexibility in the placement of resources within the microgrid, and a lower-cost implementation through incorporating peer-to-peer and plug-and play concepts.[2]

The Santa Rita Jail uses a loop distribution system as shown in Figure 2. The electrical distribution circuit is designed to provide both reliability and flexibility for electricity delivery. If a device fails, such as a transformer within the Santa Rita Jail distribution system, the device can be isolated from the distribution circuit using switches to allow remaining systems to operate. The distribution circuit is designed so that the electrical loads can be fed from two different electric busses.

[2] Derived from certs.lbl.gov/certs-der-micro.html

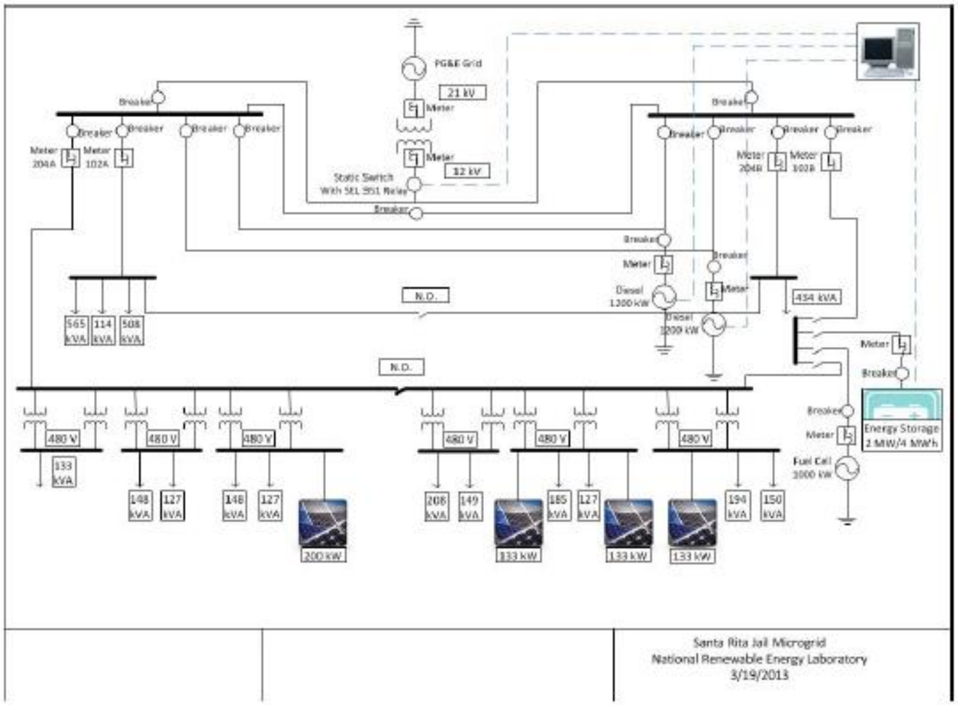

Figure 2: Santa Rita Jail electric distribution system

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2 Description of Monitoring, Data Acquisition, and Load Control Strategy

This section describes the equipment used to collect data, and the load control strategy used by the microgrid. It also recommends steps to improve the security and operation of the microgrid.

2.1 Metering

The metering at the site includes two main power meter types: ION 6200 meters are used for measuring power and energy, and ION 7650 meters are used for measuring power quality. Each meter is currently set to measure in 15-minute intervals, but they have the capability for more frequent measurements through a programmable interface, including event triggering. The types of measurement and communications available for the two power meters are given in Table 2 and Table 3.

Table 2: ION 6200 power meter

Measurements	Voltage L-N Voltage L-L Frequency Current kW kWh PF Voltage THD Current THD
Communications	Modbus RS-485

Table 3: ION 7650 power quality meter

Measurements	Power, energy, demand Harmonics Symmetrical components: zero, positive, negative Flicker Time Stamp
Communications	IEC 61850 RS-232/485; Ethernet; optical Internal Modem DNP 3.0 Modbus; Modbus TCP EtherGater, Modem Gate, MeterM@il, WebMeter Relay outputs

Figure 3 is a diagram showing control and metering for the microgrid; ION 6200 power meters are indicated by "E" and ION 7650 power quality meters are indicated by "PQ."

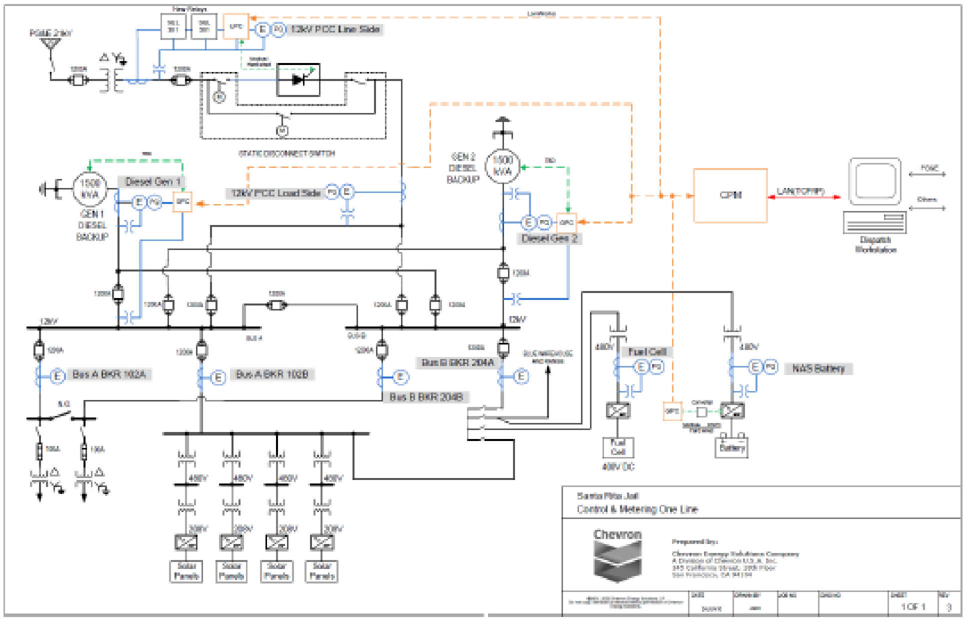

Figure 3: Control and metering diagram

2.2 Network and Servers

The communication network for the microgrid contains components from both Encorp and Applied Power Technologies, Inc. (APT). Encorp installed "Gold Boxes"—programmable logic controllers (PLC)–for the static switch, the diesel generators, the energy storage system, and the load control. They provide the hardware interface between meters, relays, human-machine interface devices, servers, and other equipment.

APT provided the power meters and programmed the PLC for control of the energy storage. APT provided a server that acts as a supervisory controller and stores power data from the microgrid meters, and can display power data in real time.

2.3 Load Control Strategy

The Encorp control system includes a method for load shedding. The loads are classified into three categories: 'A,' 'B,' and 'C'. 'A' loads are the most critical loads, 'B' loads are the next most critical loads, and 'C' loads are the least critical loads. The controllable loads can be manually reclassified at any time.

The microgrid control defines which loads will be connected under various conditions. The load control strategy is complex, due to the number and variety of connected generation and storage equipment types. The battery state of charge (SOC) can influence which loads are connected or disconnected. If, for example, power from the utility is lost and the microgrid disconnects from the utility, all loads may continue to be connected, unless the battery SOC falls below a programmed set point (“lo”), at which point ‘C’ loads are shut off, while ‘A’ and ‘B’ loads remain connected to the microgrid sources. If the battery falls below a second set SOC (“lo lo”), the ‘B’ loads will also be disconnected, and will not be reconnected unless the battery SOC rebounds above the “hi” setpoint.

2.4 Recommendations for Metering and Monitoring

Based on our review of the Santa Rita Jail microgrid, we feel that the following changes have potential to improve the operation and security of the system:

- Develop procedures for the operations staff to follow if the communications or supervisory control systems fail
- Perform regular security audits and maintain software revision control as the system undergoes software and hardware upgrades
- Perform regular tests or drills to confirm that systems operate properly under various scenarios
- Provide a redundant server that can take control in real-time should the primary server fail
- Calibrate meters and sensors on a cycle specified by the equipment manufacturers
- Add a weather station that includes solar irradiance sensing and full sky imagery to determine PV operational efficiency
- Instrument or provide a means to collect data on un-monitored PV systems at the site together with the other microgrid data

3 System Modeling and Analysis

In this section, we discuss simulation and modeling performed by NREL, the purpose of which was to explore the impact of increased generation capacity on the battery system, and to estimate the potential for energy cost reductions.

3.1 Simulations and Software

Two software tools were used in this modeling effort: HOMER and PVWatts. HOMER is a software simulation tool[3] that can be used to determine—using hourly or 15-minute historic or calculated loads, equipment costs and simulated power output—equipment sizes, and overall dispatch operation, that will optimize economic performance of a microgrid.

The solar production profile for the site was estimated using another NREL-developed software tool—PVWatts—and yearly solar irradiance data for the site. PVWatts approximates solar output of a theoretical PV array based on past irradiance data for sites across the world. An irradiance meter located close to Dublin, CA was used to estimate the yearly irradiance data.

3.2 Battery system sizing

A HOMER simulation study was conducted to estimate necessary energy storage sizes for increasing generation capacity of the fuel cell and/or the PV arrays, using a one-hour time step. The primary simulation inputs used are shown in Table 4.

Table 4: HOMER simulation inputs and outputs

Inputs	Wind resources Solar resource Electric costs from PG&E Schedule E-20 (Table 7) Diesel operation Natural gas costs for fuel cell (Table 6) Wind operation and maintenance costs Solar operation and maintenance costs Fuel cell operation and maintenance costs Energy storage operation and maintenance costs
Outputs	Operation of loads and generation

HOMER uses yearly profiles for each source. At the time the simulation was conducted, only two days of data for the Santa Rita Jail were available, July 17, 2012 and July 18, 2012[4]. This data was scaled based on a yearly load profile that PG&E publishes on their website to describe the average dynamic load profiles for each of its rate customers. The two days of measured data is shown in Figure 4.

The PV system size was adjusted to match the solar output from the data in Figure 4. As a result, the PV system was modeled as a single 550-kW PV system. This represents the amount of PV power the site is currently producing, which is much less that the rated power.

[3] HOMER was originally developed at NREL; it is now available at http://www.homerenergy.com/

[4] Additional site load was received after the HOMER simulations were performed. That data is used for analysis of actual operation in this report.

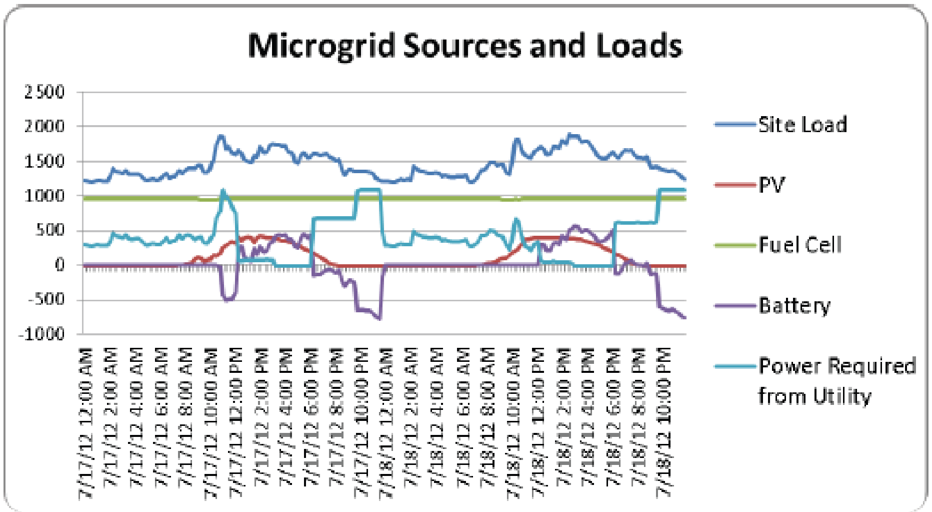

Figure 4: Site load and microgrid energy sources

The HOMER simulation was used to predict the minimum power and energy storage capacities required for the battery system to prevent exporting power to the utility. This power could be generated by the existing fuel cell and PV systems or by new sources. The analysis assumed that the PV and fuel cell power could not be modulated or controlled to match the estimated scaled electrical site load described above.

HOMER was used to simulate operations for a period of one year. Figure 5 through Figure 8 show the days that would have the greatest impact on the energy storage requirements, for the given generation scenario.

The plot labeled "Excess Electricity" in each of the figures represents the expected generation exceeding the on-site demand; this generation would either need to be curtailed or stored, assuming export to the utility is not allowed.

The energy required by the battery was estimated by integrating the area under the "Excess Electricity" curve. The plot labeled "AC Primary Load" is the approximate site load—generated and scaled as discussed previously. The plot labeled "PV Power" is the approximate PV electric power output. The plot labeled "Fuel Cell Power" is the electrical power output of the fuel cell.

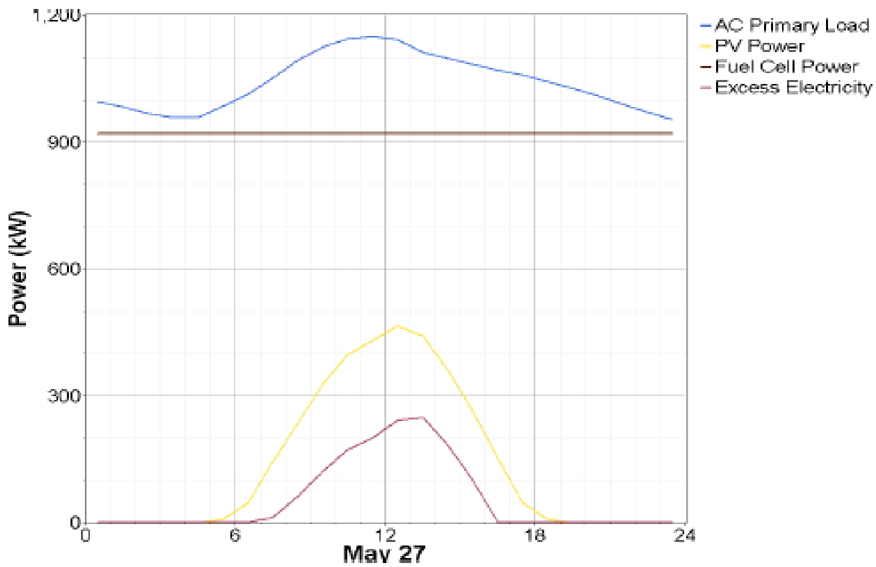

Figure 5: HOMER simulations for baseline PV and fuel cell

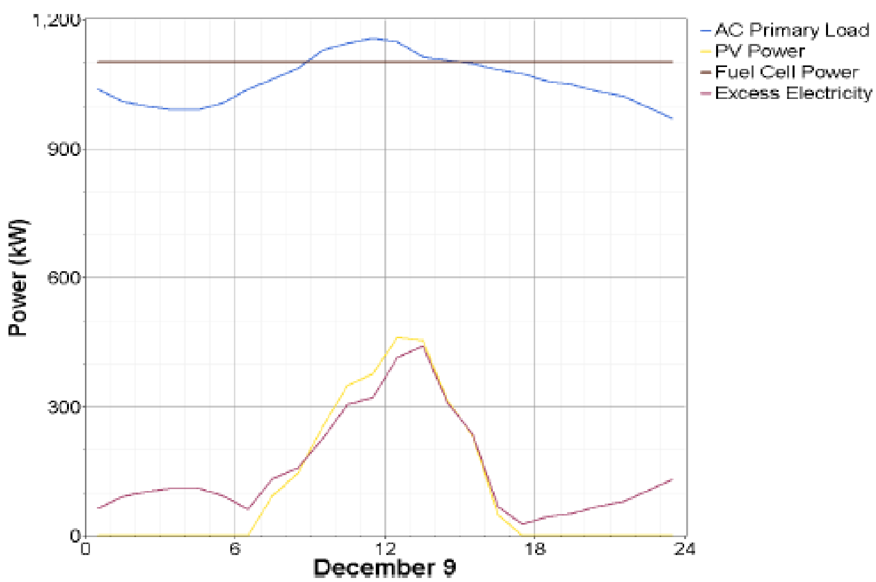

Figure 6: HOMER simulations for 1,100 kW fuel cell and baseline PV

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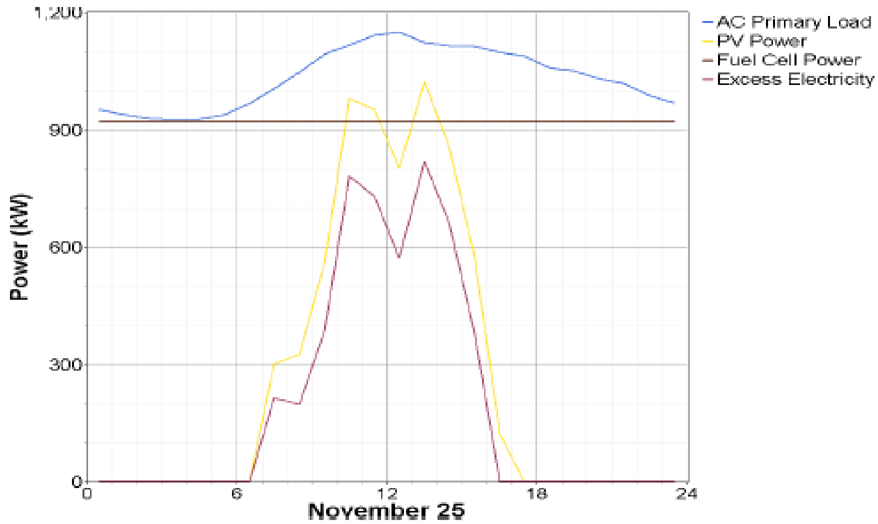

Figure 7: HOMER Simulations for Baseline Fuel Cell and 1,200 kW PV

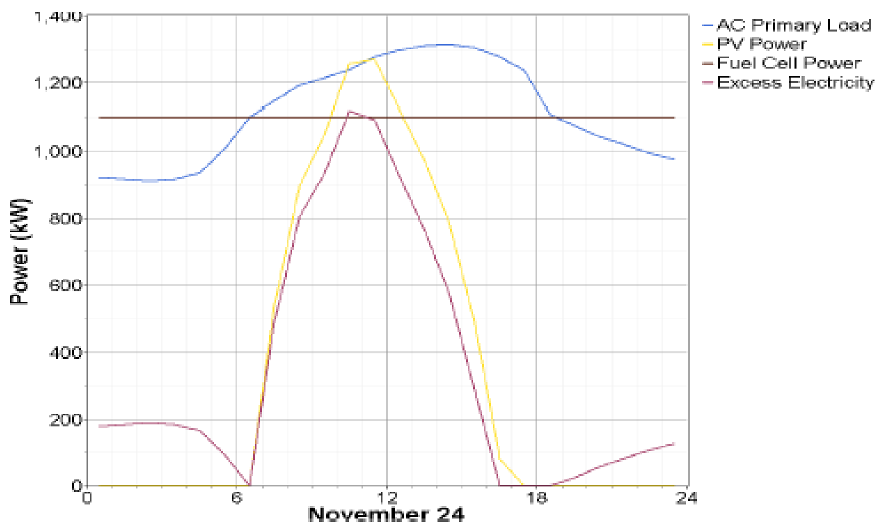

Figure 8: HOMER simulations for 1,100 kW fuel cell and 1,200 kW PV

Table 5 provides a summary of the simulation results and estimated energy storage requirements for a few combinations of additional PV and fuel cell generation resources.

Table 5: Estimated energy storage as a function of fuel cell and PV size

Fuel Cell Size	PV Operation	Required Energy Storage	Figure Reference
950 kW	550kW (existing)	500 kW, 3 MWh (existing)	Figure 5
1100 kW	550 kW (existing)	1 MW, 5 MWh	Figure 6
950 kW	1.2 MW output	2 MW, over 5 MWh	Figure 7
1100 kW	1.2 MW output	2 MW, 10 MWh	Figure 8

It should again be noted that actual loads for a year were not available at the time the HOMER simulation was conducted[5]. Future dynamic simulations could be conducted using actual yearly load data to evaluate existing and future generation resource scenarios and control methodologies.

3.3 Potential energy savings

The output of the HOMER simulations for the current configuration was used to estimate the potential monthly electrical energy savings that the microgrid generation assets provide during grid-connected operations. Figure 9 provides an estimate of the electrical energy reduction in terms of kWh due to the microgrid generation and Figure 10 shows the dollar savings. The results are shown by time period used to bill for energy charges according to the E-20 rate structure shown in Table 7, on page 23.

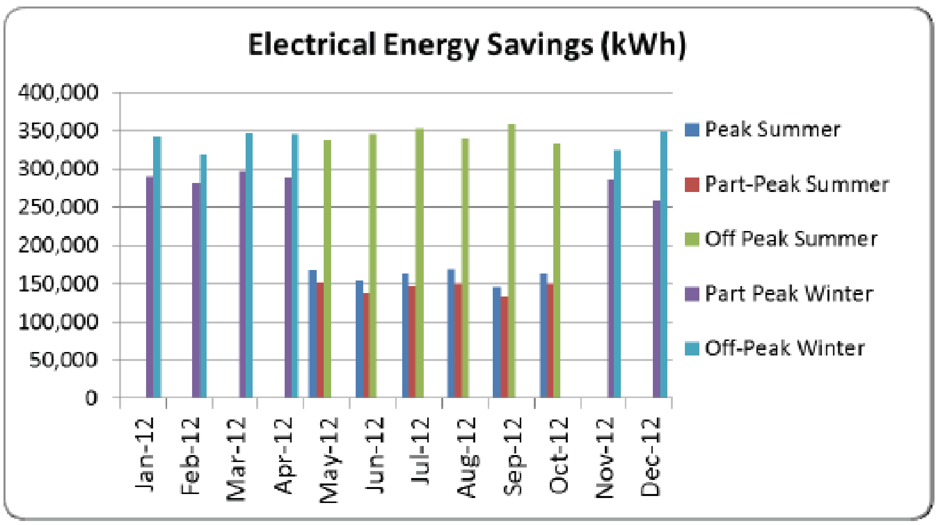

Figure 9: Estimated monthly energy savings (kWh)

[5] Additional data was acquired in March, 2014; this data is used in the loads analysis, but the HOMER simulation has not been updated

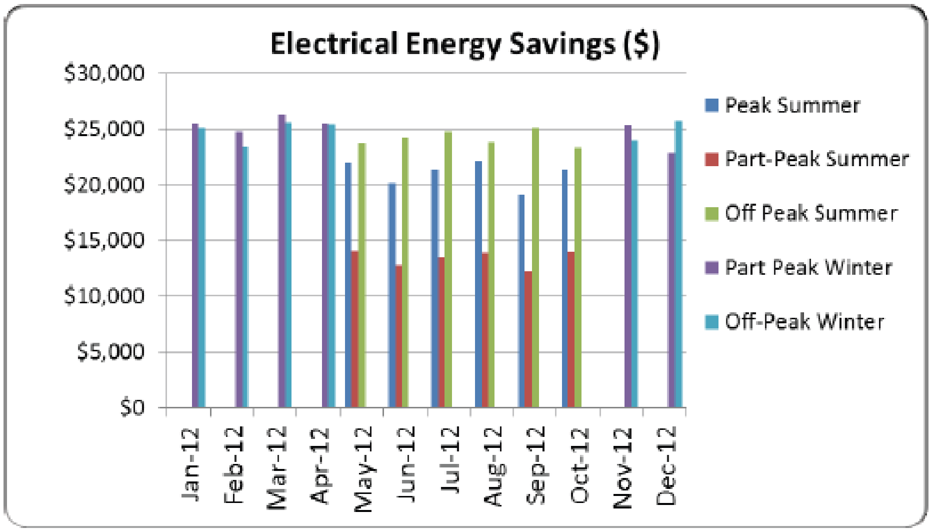

Figure 10: Estimated monthly electrical energy cost savings ($)

It can be seen that the part-peak winter and off-peak winter energy cost savings are similar. During the summer months, the off-peak savings is the largest followed by the savings due to the peak summer rate. The lowest savings is the part-peak summer savings.

4 Santa Rita Jail Energy Use and Cost

In this section we analyze the jail's energy use and cost. We start by looking at natural gas—which is used by the fuel cell—and then analyze electricity use and costs. We also estimate how much money could be saved if all grid resources were performing as expected, and compare the results to actual savings. The section finishes with recommendations for further optimization of the microgrid distributed resources.

4.1 Natural Gas Use and Cost

The fuel cell accounts for a significant portion of the jail's natural gas use. Table 6 provides the natural gas use and costs for the period of July 2011 through January 2013, for the fuel cell and for the rest of the facility (not including the fuel cell).

Table 6: Santa Rita Jail monthly natural gas consumption and cost

		Fuel cell			Rest of facility		
Period starting	Bill period (days)	Natural gas usage (therms)	Natural gas cost ($)	Natural gas unit cost ($/therm)	Natural gas usage (therms)	Natural gas cost ($)	Natural gas unit cost ($/therm)
6/30/2011	31	27,359	$15,313	$0.560	37,610	$25,406	$0.676
7/31/2011	31	64,248	$35,370	$0.551	35,818	$23,867	$0.666
8/31/2011	30	47,907	$26,329	$0.550	32,210	$21,433	$0.665
9/30/2011	31	35,549	$19,112	$0.538	36,312	$23,728	$0.653
10/31/2011	30	29,044	$14,461	$0.498	67,422	$43,129	$0.640
11/30/2011	31	40,130	$19,670	$0.490	87,182	$55,095	$0.632
12/31/2011	31	66,520	$31,189	$0.469	85,841	$53,697	$0.626
1/31/2012	29	50,981	$23,382	$0.459	71,758	$44,153	$0.615
2/29/2012	31	54,654	$24,072	$0.440	67,294	$40,182	$0.597
3/31/2012	30	60,474	$25,196	$0.417	51,203	$27,978	$0.546
4/30/2012	31	60,088	$25,876	$0.431	52,520	$29,488	$0.561
5/31/2012	30	59,122	$28,149	$0.476	39,565	$23,972	$0.606
6/30/2012	31	65,396	$30,094	$0.460	36,848	$21,739	$0.590
7/31/2012	31	65,912	$31,633	$0.480	31,969	$19,492	$0.610
8/31/2012	30	53,134	$24,360	$0.458	26,143	$15,379	$0.588
9/30/2012	31	62,219	$29,661	$0.477	32,377	$19,637	$0.607
10/31/2012	30	54,756	$27,025	$0.494	54,725	$35,584	$0.650
11/30/2012	31	59,997	$29,553	$0.493	91,547	$59,437	$0.649
12/31/2012	31	59,994	$27,688	$0.462	112,297	$66,874	$0.596

4.2 Electric Utility Data and Rates

Alameda County provided NREL with operational data for microgrid operations—including power drawn from the utility, and power provided by the on-site distributed resources (battery system, PV arrays, fuel cell and wind turbines)—covering the two-year period that began in

January 2012.[6] Note that, as a result of how the meters are set up, the facility power was calculated by adding the utility power to that of the distributed energy resources.

Electric billing from the utility, PG&E, consists of several components, the most significant of which are *electric demand* and *electric energy consumption*. These are discussed in separate sections, below.

Table 7[7] gives a summary of rates that PG&E charges during various seasons and time intervals. The data for the table is based on the E-20 rate structure, which can be found on PG&E's web site. The highest utility costs for both demand and energy occur between noon and 6PM, Monday through Friday, during the summer; during those hours the peak demand charge is $15.40/kW and the peak energy charge is $0.13097/kWh.

Peak demand charges during the summer are a function of maximum demand, part-peak demand, and peak demand for the month. During winter, only maximum demand and maximum part-peak demand are determined each month. Similarly for energy charges, summer days have three time periods with different rates, whereas winter days have only two.

Table 7: PG&E electricity rate schedule E-20 Primary (Oct 2012-Apr 2013)[7]

Rate Name	Times	Days	Rate
Peak demand rates			
Maximum Demand Summer			$9.33/kW
Maximum Part-Peak Demand Summer	8:30 a.m. to 12:00 noon and 6:00 p.m. to 9:30 p.m.	Monday-Friday except holidays	$3.23/kW
Maximum Peak Demand Summer	12:00 noon to 6:00 p.m.	Monday-Friday except holidays	$15.40/kW
Maximum Demand Winter			$9.33/kW
Maximum Part-Peak Demand Winter	8:30 a.m. to 9:30 p.m.	Monday-Friday except holidays	$0.25/kW
Energy rates			
Part-Peak Summer	8:30 a.m. to 12:00 noon and 6:00 p.m. to 9:30 p.m.	Monday-Friday except holidays	$0.09268/kWh
Peak Summer	12:00 noon to 6:00 p.m.	Monday-Friday except holidays	$0.13097/kWh
Off-Peak Summer	9:30pm to 8:30 a.m. and all day on weekends and holidays		$0.07028/kWh
Part-Peak Winter	8:30 a.m. to 9:30 p.m.	Monday-Friday except holidays	$0.08835/kWh
Off-Peak Winter	9:30 p.m. to 8:30 a.m. and all day on weekends/holidays		$0.07376/kWh

Note: PF Adjustment rate ($/kWh/%): $0.00005/kWh/%

Note: Summer (May 1 to October 31), winter (November 1 to April 30)

[6] The battery system was added in February of 2012, but in the files received from Alameda County, the battery power was not included in the calculation of the total demand in February, March or April of 2012. NREL modified the files for March and April to include the battery power (the battery did not draw/provide any significant power until March, so this had an insignificant impact in February).

[7] The rates shown in the table were valid for October 2012 to April 2013. Rates are adjusted each year in May and in October, and varied over the time period of the study. Actual values were used in this analysis.

In addition to demand and energy charges, the power factor (PF) charge is \$0.00005/kWh/%. The rate states:

> The rate charges (based on actual utility bill for the site) are adjusted based upon the power factor. The power factor is computed from the ratio of lagging reactive kilovolt-ampere-hours to the kilowatt-hours consumed in the month. Power factors are rounded to the nearest whole percent. The rates in this schedule are based on a power factor of 85 percent. If the average power factor is greater than 85 percent, the total monthly bill will be reduced by the product of the power factor rate and the kilowatt-hour usage for each percentage point above 85 percent. If the average power factor is below 85 percent, the total monthly bill will be increased by the product of the power factor rate and the kilowatt-hour usage for each percentage point below 85 percent. Power factor adjustments will be assigned to distribution for billing purposes.

For example, if the average power factor—as calculated from readings by the meter used for billing at the point of common coupling (PCC)—was 70 percent for the month of March 2013, during which the utility provided a total of 513,053 kWh, the power factor charge would be

$$\$0.00005/\text{kWh}/\% \times 513{,}053\ \text{kWh} \times (85\%-70\%) = \$384.79$$

This is a relatively small amount and the power factor charges are therefore not included in the cost analysis presented in this report.

4.3 Electricity Use and Cost

As discussed above, the jail has two main sources of electrical energy: the electric utility grid (PG&E) and the on-site distributed energy resources. Figure 11 shows a diagram of the microgrid, with directions of positive power flow for each component indicated by arrows. Note that for the battery, positive power flow indicates discharging. Renewable energy sources are shown as green boxes (solar and wind); the fuel cell (which is fuelled by natural gas) is shown in orange, and the energy storage (battery) system in light blue. The diesel generators are not shown, since they are not operated in grid-connected mode.

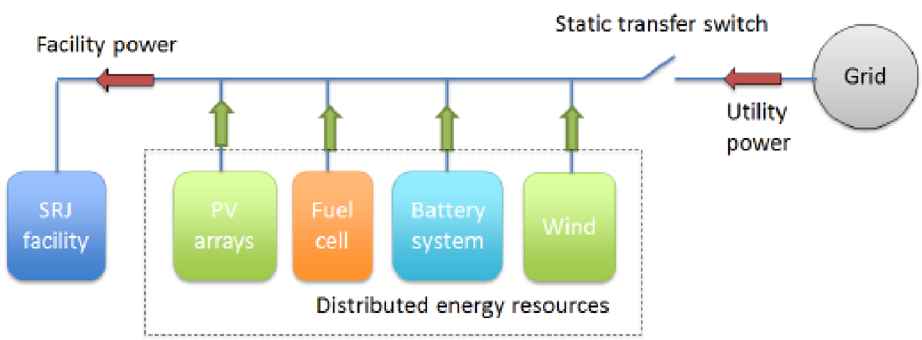

Figure 11: Major energy sources for the Santa Rita Jail microgrid

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4.3.1 Electric peak demand

Electric demand, or electric load, refers to the average electric power used over a 15-minute interval. For this analysis, peak demand for the *utility power* and for the *facility power*, as indicated by the red arrows in Figure 11, are considered.

The facility has a winter base load demand of approximately 1.5 MW; during the summer months a cyclical load—most likely attributable to air conditioning—adds approximately 500-kW, resulting in a peak load of approximately 2 MW. The highest demand observed—just under 2.5 MW—was recorded on July 2nd, 2013, at 3 pm.

Figure 12 shows the facility power demand during a cool-weather week (2/1/13 through 12/7/13), which exhibits typical winter base load of approximately 1.5 MW.

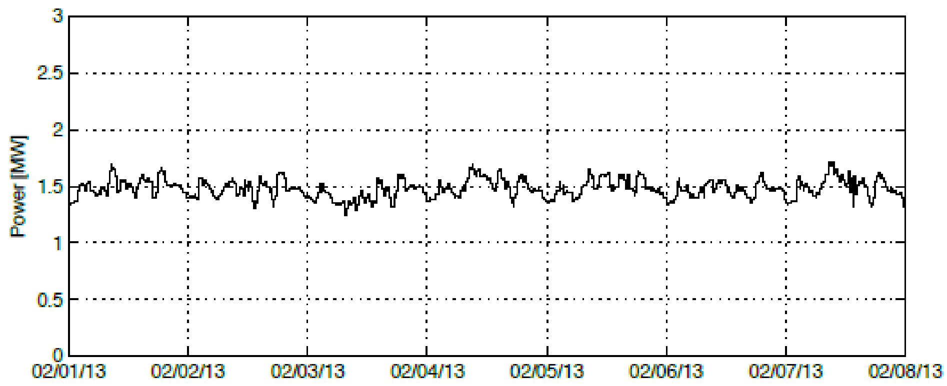

Figure 12: Week with typical winter base load demand

Table 8 shows the temperature data for the same week as above. Note that the highest temperature for the week was 65°F, so air conditioning probably would not have been required.

Table 8: Temperature data for week of February 1st, 2013

Date	Max temp (°F)	Mean temp (°F)	Min temp (°F)
2/1/2013	64	51	37
2/2/2013	62	52	41
2/3/2013	60	51	41
2/4/2013	65	51	36
2/5/2013	55	50	44
2/6/2013	61	49	37
2/7/2013	55	45	34

Figure 13 shows the week (7/1/13 through 7/7/13) with the highest 15-minute-interval facility power demand for the site—2.456 MW on July 2nd.

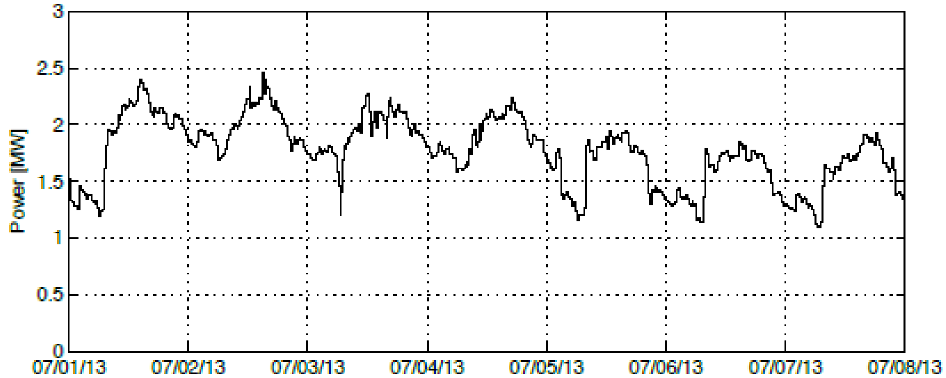

Figure 13: Week with highest 15-minute total demand

Table 9 shows temperature data for the first week of July, 2013. Note that the daily high temperatures were over 100°F at the beginning of the week, dropping off on the 5th and 6th, which corresponds with power demand seen in Figure 13.

Table 9: Temperature data for week of July 1st, 2013

Date	Max temp (°F)	Mean temp (°F)	Min temp (°F)
7/1/2013	103	84	64
7/2/2013	103	85	66
7/3/2013	102	83	64
7/4/2013	103	86	69
7/5/2013	78	68	57
7/6/2013	84	70	56
7/7/2013	90	72	54

The power drawn from the utility equals the facility power minus the power delivered by the distributed energy resources (see Figure 11 for clarification). When the total demand is met by the distributed resources, the utility power reaches zero. This happens most often during on-peak hours, when the battery is discharged to reduce costs associate with high energy fees. The site is not allowed to export power, and the control strategy is designed to prevent the flow of power from the microgrid to the utility. Figure 14 shows utility power, and battery charging and discharging, for the week of 5/13/2013 through 5/19/13. (Negative battery power indicates that the battery is charging, and positive indicates that the battery is supplying power to the site loads.) Note that there are several instances where the controller uses the battery system to reduce the power demand from the utility to zero.

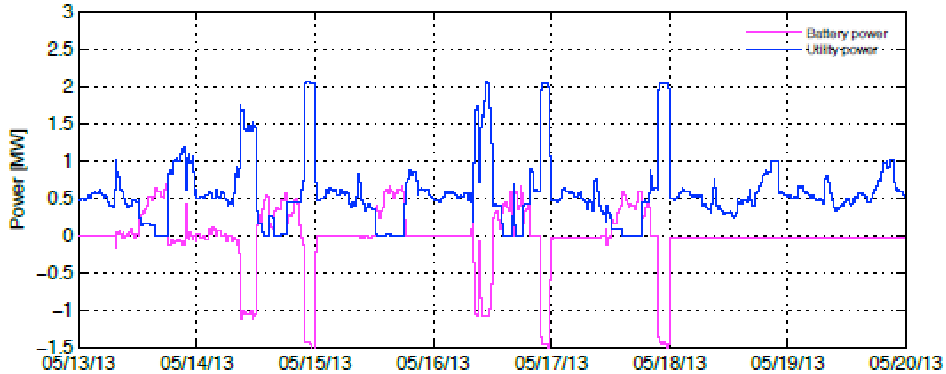

Figure 14: Utility and battery data (5/13/2013 to 5/19/2013); includes instances of battery discharging to achieve zero utility power during on-peak hours, and battery charging during off-peak hours

Figure 15 shows data for the week with the highest 15-minute-interval power demand from the utility— 7/1/13 through 7/7/13. The maximum demand from the utility—2.84 MW—occurred on July 1st. The facility power was at its peak this week, and the fuel cell was not operating on July 1st, resulting in the utility providing almost all of the facility. When the control system charged the batteries under these conditions, the demand from the utility exceeded the peak facility power demand for the month, resulting in increased peak demand charges.

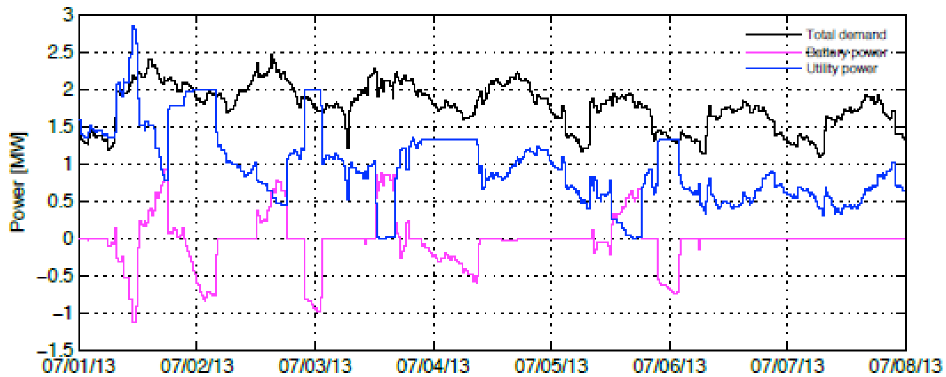

Figure 15: Week with highest 15-minute-interval power demand from the utility

Occasionally, the utility power exceeded 2 MW during a battery charging event, an example of which can be seen in Figure 15 on July 1st. This only occurred four other times during the two years for which data was analyzed: twice more in July 2013, and a previous two times in November 2012.

When grid-connected, the microgrid distributed energy resources supplement the utility resources to serve the jail's electrical load. Figure 16 shows the calculated reduction in peak utility demand and Figure 17 shows the calculated cost savings from that reduction. The peak demand reduction is calculated by subtracting the peak utility demand from the peak facility demand, since the utility power would be equal to the facility power in the absence of the distributed energy resources. This is done for each of the relevant categories listed in Table 7, on page 23.

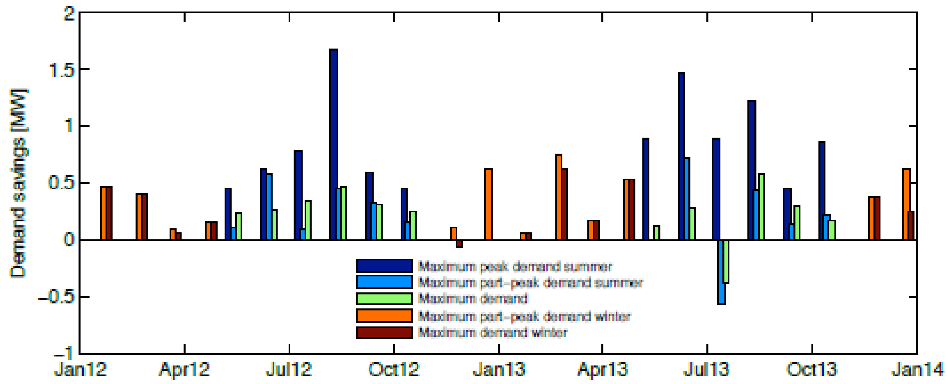

Figure 16: Calculated monthly demand savings (MW)

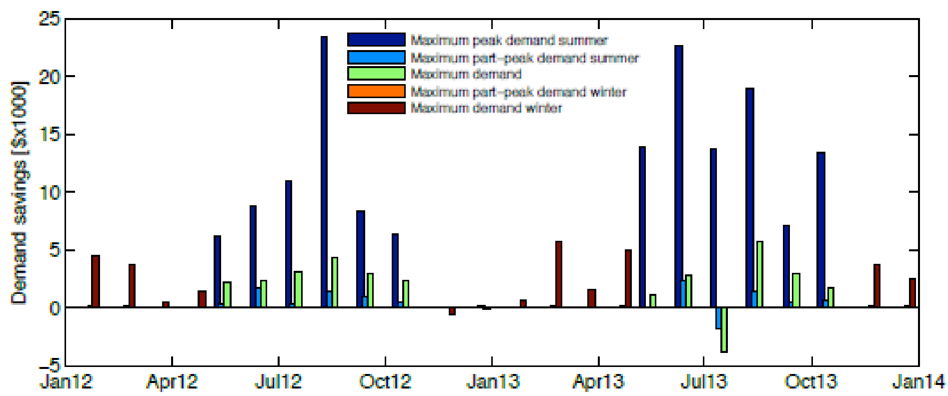

Figure 17: Calculated monthly demand savings ($)

The reduced demand is primarily due to the fuel cell and PV power generation. If the fuel cell were to operate continuously at its rated power of 1 MW, this would reduce utility power demand by 1 MW at all times. However, the demand savings are generally far less than this. Because demand is billed based on the 15-minute period with the highest demand in each category (overall and over specific time periods in the day) for each month, the loss of fuel cell output for any length of time could potentially reduce the demand savings achieved. The only month in which the fuel cell operated continuously was August 2012, and the highest demand saving was achieved that month. The next highest demand savings was achieved in June 2013 when the fuel cell only operated well below its normal operating point for about half a day.

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Generally the battery is charged during off-peak hours, i.e. after 9:30 pm, as shown in Figure 14 and Figure 15. It may also charge to prevent export of power to the grid at other times. At times, the utility power during a regular, off-peak, charging event is close to the peak demand from the utility for that month, which reduces the demand savings. If a lower charge rate is used, more demand savings could be achieved. The off-peak charge cycles are short, generally less than three hours, so a lower charge rate is feasible while still ensuring that the battery is fully charged by the start of the next part-peak period. During July 2013 and November 2012, charging events resulted in utility power demand that was higher than the peak facility power demand for the month. This is reflected in negative demand savings for the month.

4.3.2 Electric energy consumption

Electric energy costs are determined by the amount of energy delivered by the utility and the time periods during which the energy is delivered, since different rates apply. The microgrid distributed energy resources can reduce electric energy purchased from the grid, thereby reducing utility charges.

Figure 18 shows the calculated energy savings due to the operation of the microgrid for a two-year period. Energy savings was calculated by subtracting the energy delivered by the utility from the energy delivered to the SRJ facility.

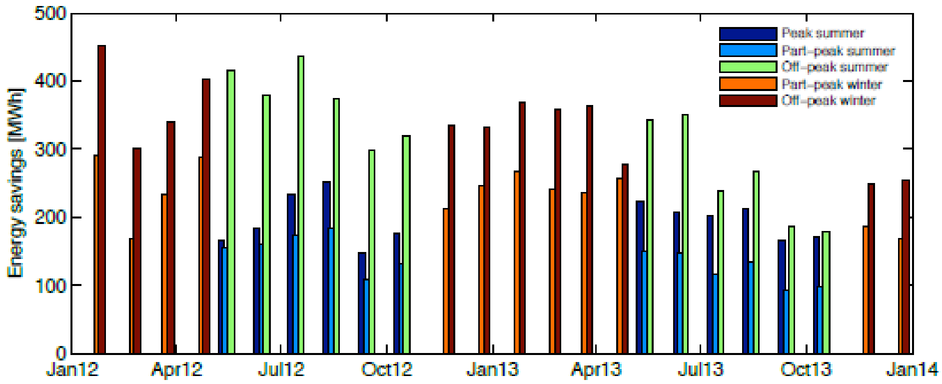

Figure 18: Calculated monthly energy savings (MWh)

Figure 19 shows the cost savings resulting from the electrical energy savings discussed above (natural gas costs are not included in these savings).

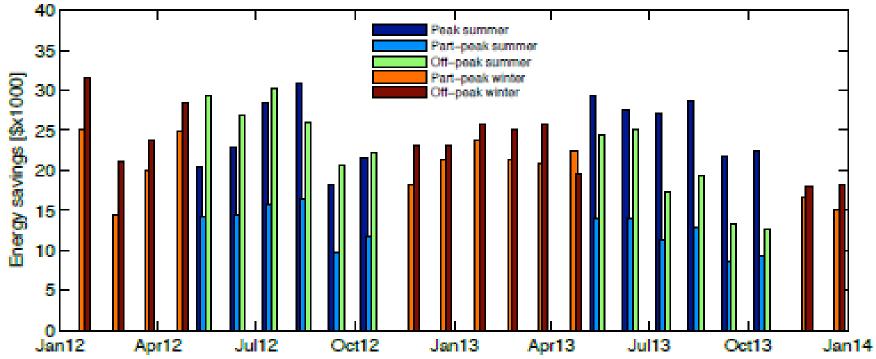

Figure 19: Calculated electrical energy cost savings ($)

The actual energy and energy cost savings are similar to what was estimated through the HOMER simulations, as described in Section 3.3 The actual energy savings were lower in 2013 than in 2012—in large part due to the fact that the fuel cell output was consistently lower than its rated power, when operational, as shown in Table 10.

Table 10: Approximate fuel cell output, 2012-2013

Period	Output when operational [kW]
January-July 2012	1,000 (except for part of March 2012 it was operated at about 600 kW)
August-October 2012	900
November 2012-June 2013	800
July-September 2013	700
Last half of October 2013	500
November and December 2013	600

4.4 Total Savings Due to Microgrid Distributed Resources

The net energy delivered to the facility by the distributed resources was 7,899 MWh in 2012 and 6,708 MWh in 2013. This represents 60% and 49% percent of the total energy used by the facility in 2012 and 2013 respectively. This resulted in savings on energy charges of $654,228 in 2012, and $590,145 in 2013, for a total of $1,244,373—though this does not account for the cost of natural gas for the fuel cell.

Savings due to peak demand charges were $95,880 in 2012 and $122,640 in 2013.

The cost savings due to reduced energy consumption—and from time-shifting to lower rate periods—is almost six times greater than the savings due to utility demand reduction, (again, not accounting for the cost of natural gas used by the fuel cell). This ratio is particularly high since the actual demand savings were lower than the potential demand savings, as discussed previously, while the actual energy savings were much closer to the potential energy savings.

The total cost savings is calculated by adding the demand savings, (i.e. the reduction in demand charges paid to the utility), to the energy savings, and subtracting the cost of the natural gas to operate the fuel cell.

The total cost savings was $447, 204 in 2012 and $378,132 in 2013, for a total of $825,336 over two years. Savings in 2013 decreased from 2012 due to the fuel cell being operated at lower output levels in 2013 (we don't know if this was due to operational problems with the fuel cell, higher natural gas prices, or some other factor.

Figure 20 shows the energy and cost savings, total cost savings, and the natural gas costs, for 2012 and 2013.

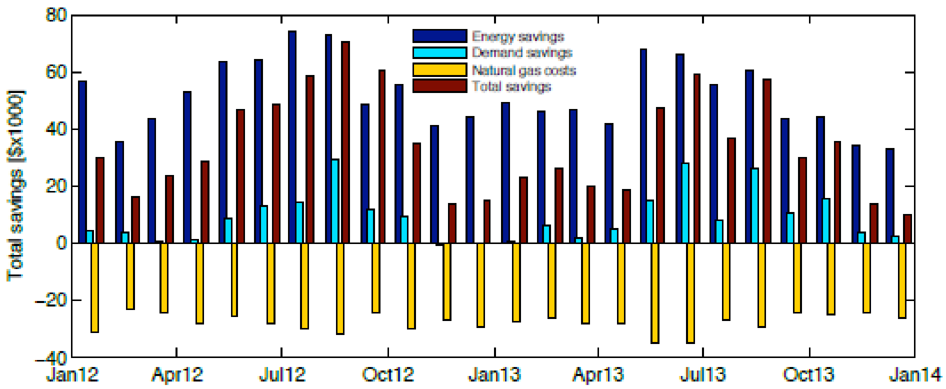

Figure 20: Total cost savings ($)

4.5 Recommendations

1. Operate the chiller as part of the regular load control during grid connected operation and use the chiller's soft start option.

2. Reduce downtime of the fuel cell and operate close to rated power.

3. Adjust the battery system control operation to reduce the demand by, e.g., charging at lower rate during off-peak times, and prepare it to participate in PG&E's demand response program.

4. Improve the power factor to reduce power factor adjustment charges. The battery and future PV systems could provide VAR support and/or capacitors may be added to the site.

5. Operate the diesel generators for maintenance during peak rate times, if operating permits allow.

5 Conclusions and Key Findings

5.1 Conclusions

This report provides an analysis of the economic benefits of grid-connected operation of the Santa Rita jail microgrid in Alameda County, California. The microgrid includes a fuel cell, photovoltaic (PV) arrays, a battery system, wind turbines and load control. The analysis covers data collected over a two year time period, starting in January 2012. In addition, system modeling was performed in HOMER software to estimate potential energy savings and the battery system capacity required to support fuel cell and PV generation capacity increases.

The analysis of measured data show that the microgrid, in addition to providing power to critical loads during utility outages, provided economic benefit through utility bill savings of $447,204 in 2012 and $378,132 in 2013. This was primarily achieved through reducing the energy required from the utility by using on-site distributed energy resources, including PV arrays, wind turbines and a fuel cell. In 2012, the microgrid energy sources provided 60% of the electrical energy used by the facility, resulting in energy cost savings of $654,228, and provided 49% of the facility energy, resulting in energy cost savings of $590,145 in 2013.

Further reductions in utility charges, of $95,880 and $122,640 in 2012 and 2013 respectively, were achieved by reducing the peak demand from the utility through using the aforementioned resources in conjunction with a battery system that provides power during peak hours, charges during off-peak hours, and prevents export of power from the microgrid to the utility. The demand savings are significantly less than the energy savings, in part due to its sensitivity to interruptions in the operation of the fuel cell, since demand is charged based on the peak power over a 15 minute interval during the month.

5.2 Key findings

- The microgrid provides economic benefit through reduction in utility bills, in addition to providing back-up power to critical loads during an outage. Total cost savings attributable to the microgrid were over $447,000 in 2012 and $378,000 in 2013.
- The economic benefit can be increased by reducing the downtime of the fuel cell and by operating it closer to its rated power. To this end, it is recommended to add redundancy to the microgrid control system.
- Additional increases in utility bill savings can be achieved by adjusting the battery system control operation to charge at a lower rate during off-peak times so as to reduce the peak utility power demand.

Appendix A: PG&E Demand Response Programs (2013)

Table 11 provides a description of each demand program (from PG&E's website).

Table 11: PG&E demand response programs 2013

Program	Incentive	Requirement	Website
Peak Day Pricing (PDP)	**Reduced Rates**	Customers who participate in PDP will experience between 9 and 15 PDP Event Days annually in addition to time-of-use pricing. On PDP Event Days, a surcharge is added to a portion of the peak period (i.e., from 2 p.m. to 6 p.m.) which customers will pay in addition to their regular peak electric rate.	http://www.pge.com/mybusiness/energysavingsrebates/timevaryingpricing/peakdaypricing
Base Interruptible Program (BIP)	**$9/kW**	BIP gives you 30 minutes advance notice. You will receive a monthly incentive payment even if no events are called. However, failure to reduce load down to or below your Firm Service Level during an event will result in a charge of $6.00/kWh for any energy use above the Firm Service Level. There is a maximum of one event per day and four hours per event. The Program will not exceed 10 events per month, or 120 hours per year.	http://www.pge.com/mybusiness/energysavingsrebates/demandresponse/baseinterruptible
Demand Bidding Program (DBP)	**$0.50/kW or $0.60/kW**	For day-ahead events, you will receive an event notice by noon on the business day before the planned event. You will have until 3 p.m. that day to submit bids via InterAct. For day-of events, you will have one hour after receiving the event notice to submit bids via InterAct. PG&E will notify participants of bid acceptance within 15 minutes of the bid acceptance window closing.	http://www.pge.com/mybusiness/energysavingsrebates/demandresponse/dbp
Optional Binding Mandatory Curtailment (OBMC) Plan	**Varies**		http://www.pge.com/mybusiness/energysavingsrebates/demandresponse/obmcp
Scheduled Load Reduction Program (SLRP)		You select one to three four-hour time periods (between 8 a.m. and 8 p.m.) on one or more weekdays. You are required to reduce load each and every time your selected SLRP options (day of the week and corresponding elected time) occur. Your load reduction cannot be shifted to an on-peak time period (noon to 6 p.m.) on another day.	http://www.pge.com/mybusiness/energysavingsrebates/demandresponse/slrp
Permanent Load Shift	**Under development**		
SmartAC	**No longer available**		
Aggregator Managed Portfolio (AMP)	**Varies**	Many aggregators possible	http://www.pge.com/mybusiness/energysavingsrebates/demandresponse/amp
Capacity Bidding Program (CBP)	**Varies**	Load reduction commitment is on a month-by-month basis, with nominations made five days prior to the beginning of each month. Customers must enroll with (or as) a third-party aggregator to join the Capacity Bidding Program. 1-4 Hour: June: $4.27/kW. July: $17.94/kW. August: $24.81/kW. September: $15.30/kW.	http://www.pge.com/mybusiness/energysavingsrebates/demandresponse/cbp

Program	Incentive	Requirement	Website
Automated Demand Response	**Between $125/kW and $400/kW**	PG&E pays between $125 per kilowatt (kW) and $400 per kW of dispatchable load reduction that will be controlled by the technology, depending upon the technology category program selected.	http://www.pge.com/mybusiness/energysavingsrebates/demandresponse/adrp
Dual Enrollment	**Many options**	Varies options with PDP, BIP, DBP, OBMC, AMP, CBP	http://www.pge.com/includes/docs/pdfs/mybusiness/energysavingsrebates/demandresponse/baseinterruptable/DR_DualParticipation.pdf

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CERTS Microgrid Demonstration with Large-Scale Energy Storage and Renewable Generation
Eduardo Alegria, Tim Brown, Erin Minear, Robert H. Lasseter [Online]
http://www.pserc.wisc.edu/documents/publications/papers/2013_general_publications/Lasseter_SmartGrid_CERTS_Microgrid_Demo_2013.pdf.

APPENDIX B:
IEEE: CERTS Microgrid Demonstration with Large-Scale Energy Storage and Renewable Generation

CERTS Microgrid Demonstration With Large-Scale Energy Storage and Renewable Generation

Eduardo Alegria, *Member, IEEE*, Tim Brown, *Member, IEEE*, Erin Minear, *Member, IEEE*, and Robert H. Lasseter, *Fellow, IEEE*

***Abstract*—The Consortium for Electric Reliability Technology Solutions (CERTS) Microgrid concept captures the emerging potential of Distributed Energy Resource (DER) using an automatous plug-and-play approach. CERTS views generation and associated loads as a subsystem or a "Microgrid." The sources can operate in parallel to the grid or can operate in island, providing high levels of electrical reliability. The system can disconnect from the utility during large events (i.e., faults, voltage collapses), but also may disconnect intentionally when the quality of power from the grid falls below certain standards. CERTS Microgrid concepts have been demonstrated at the Alameda County Santa Rita Jail in California. The existing system included a 1-MW fuel cell, 1.2 MW of solar photovoltaic, and two 1.2-MW diesel generators. Adding a 2-MW, 4-MWh storage system, a fast static switch, and a power factor correcting capacitor bank enabled microgrid operation. The islanding and resynchronization methods met all Institute of Electrical and Electronics Engineers Standard 1547 and the reliability requirements of the jail.**

***Index Terms*—Advanced energy storage, distributed generation, distributed resource, islanding, microgrid, renewable energy, smart grid.**

I. Introduction

THE Alameda County Santa Rita Jail Microgrid project is a demonstration of Consortium for Electric Reliability Technology Solutions (CERTS) Microgrid concepts, [1]–[3]. The goal from a research and design perspective is to understand the potential for large commercialization of CERTS Microgrids in the future for customers with demand for reliable power. The CERTS Microgrid concept has been developed over the last 10 years with support from the California Energy Commission and the US Department of Energy. CERTS basic research focus is the design and application of automatous controls for the full range of DER component. The CERTS approach provides standard automatous controls that enable plug-and-play functionally without the need of communication or custom engineering for each application. These features minimize engineering cost and errors and maximize flexibility. Most microgrid implementations combine loads with sources and allow for intentional islanding, but rely on complex communication and control and require custom design including extensive site engineering.

CERTS concepts demonstrated to date at American Electric Power's microgrid test bed include autonomous load following, local islanding and re-synchronizing with the grid, voltage and frequency control, reduction of circulating reactive power and stable operation for microgrids with multiple DER units. These tests where done without storage or communication between units, [4]–[7]. This functionality is achieved using two droop controllers. One is a power vs. frequency droop much like the tradition droop control on generators. Protection from self-overloading drives the frequency down when the unit becomes overloaded. This results in the other sources off-loading the overloaded unit. The second droop controller is a voltage vs. reactive power controller. When there are voltage error between two or more units there can be large circulating VARS. The reactive power output provided by each source is used modifies its own voltage regulation point. This corrects for the voltage errors and minimize the circulating VARS. Alameda County Santa Rita Jail project provides a platform to extend these concepts to storage, diesel generation and energy management systems.

This project integrates existing 1.2 MW solar photovoltaic, 1 MW fuel cell and conventional diesel generators with large-scale energy storage, a static disconnect switch and a capacitor bank. The project also upgraded the controls of the generators to make them CERTS-capable. An overarching control system referred to as Energy Management System (EMS) to economically optimize was added the use of all generation sources. Refer to Appendix A for a summary of equipment details, Fig. 1.

II. Design Considerations

Prior to the Microgrid project, the Santa Rita Jail facility was susceptible to momentary utility outages and power quality events. Maintaining power free of momentary or sustained outages is critical to the safety of the officers, staff and inmates. To prevent sustained outages, diesel generators were available to power essential facility loads. However, the diesel generators relied on a load-shed system and required approximately 10 seconds to start, during which the facility had no power.

Additionally, the solar photovoltaic and fuel cell generators were unable to operate in parallel with the diesel generators. This was due to a couple of reasons. One, it is challenging for the system to maintain proper microgrid system voltage and frequency within operational limits during transitions to the back-up diesel generators. Additionally, the diesel generator

Manuscript received January 07, 2013; revised May 29, 2013; accepted October 14, 2013. Date of publication November 19, 2013; date of current version February 14, 2014. Paper no. TSG-00010-2013. The work is coordinated by Chevron Energy Solutions and funded by the U.S. Department of Energy and the California Energy Commission Public Interest Energy Research Program.

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Digital Object Identifier 10.1109/TSG.2013.2286575

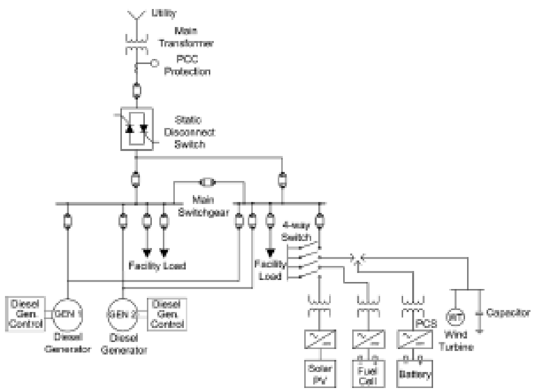

Fig. 1. Santa Rita Jail Microgrid Single Line Diagram.

frequency itself is not as stable as the grid and may trigger anti islanding functions on PV or Fuel Cell inverters to trip the equipment offline. This is a disadvantage from an economic and environmental perspective because the clean, renewable sources were not being utilized during island conditions. Upon restoration of utility power the fuel cell would take several hours to restart, resulting in increased demand and energy charges on the utility bill. The solar photovoltaic and fuel cell operation also was impacted by utility power quality events such as voltage sags, [8], [9]. These impacts related to utility issues were resolved with incorporation of a fast static disconnect switch (SDS), which enabled autonomous operation and seamless islanding of the Jail. The Jail's ability to autonomously island was key to providing the highest system reliability. Due to the practical limitations of matching the existing generation and load for a successful island transition, advanced energy storage (battery) was utilized to stabilize system voltage and frequency during transient conditions. Using CERTS Microgrid protocol aided in simplifying the integration of the battery and SDS with existing on-site resources. The "plug-and-play" nature of the CERTS protocol gives CERTS-based sources (diesel generators and battery) the ability to interconnect with each other without the need for a customized supervisory generator control system.

In addition to the battery providing system reliability and stability, it would also be used to optimize on-site generation to decrease the total cost of energy purchased from the utility. The current utility tariff schedule has time-of-use rates under which energy consumption and maximum power demand vary based on time of day and season. The battery can store energy purchased during less-expensive off-peak periods to be utilized during peak periods.

III. The CERTS Concept

One of the objectives of the CERTS Microgrid concept was to reduce microgrid system cost and increase reliability. This includes *plug-and-play* functionality without communications. Plug-and-play concepts reduce engineering cost and errors since little site modification is required for different applications. Each CERTS device regulates voltage and frequency both grid connected and while islanded. These key concepts have been demonstrated at the American Electrical Power Microgrid Test Facility. This includes such transient events such as seamless separation and automatic re-synchronizing with the grid, Class I level power quality during utility faults, large unbalanced loading and stable operation during major events [5]. The CERTS concept has three critical components: the static disconnect switch, the micro-sources, and loads. The static disconnect switch has the ability to island the microgrid autonomously for disturbances such as faults, IEEE 1547 events or power quality events. Following islanding, the reconnection of the microgrid is achieved autonomously after the tripping event is no longer present. Resynchronizing to the utility uses the frequency difference created by the islanding event [6].

Each CERTS-controlled source seamlessly balances the power on the islanded microgrid using a power vs. frequency droop controller. In this project the battery storage system and the backup diesel generators have the CERTS frequency and voltage control. The fuel cell and the photovoltaic inverters run in a power mode and do not track load, control voltage or frequency. For example, if the load increases while in island operation, the storage system will provide the extra power instantaneously and reduce the operational frequency. At maximum output the frequency controls are designed to drop no more than 1%. If there is inadequate energy to meet the load, the frequency will drop below the normal operating range, signaling the non-critical loads to shed. The coordination between sources and loads is through frequency.

The storage inverters and the diesel generators not only control the voltage but they also ensure that there are no large circulating reactive currents between units. With small errors in voltage set points, the circulating current can exceed the ratings of the units. This situation requires a voltage vs. reactive power droop controller so that, as the reactive power, Q, generated by the unit becomes more capacitive, the local voltage set point is reduced. Conversely, as Q becomes more inductive, the voltage set point is increased. At Santa Rita Jail this droop is 5%. In addition to the system voltage stability demonstrated at the AEP test site extensive analyses indicates that microgrid's stability is independent of the number of CERTS devices in a microgrid [7]. Theoretically the system remains stable as we approach an infinite number of CERTS units.

The CERTS Microgrid controls do not rely on a "master" controller or source. Each source is connected in a peer-to-peer fashion with a localized control scheme implemented for each component. This arrangement increases the reliability of the system in comparison to having a master-slave or centralized control scheme. In the case of master-slave controller architecture, the failure of the master controller could compromise the operation of the whole system. Santa Rita Jail uses a central communication system to dispatch storage set points, voltage and power as needed to control the state of charge. However, this communication network is not used for the dynamic operation of the Microgrid. This plug- and-play approach allows for expansion of the Microgrid to meet the requirements of the site without extensive re-engineering. Plug-and-play implies that a unit can be placed at any point on the electrical system without re-engineering the controls, thereby reducing the chance for engineering errors.

IV. Design Implementation

The key considerations for the Microgrid system design were meeting the criteria for operation under the CERTS protocol and integrating with the existing infrastructure.

A. Battery

The battery technology selected for this project was a 2-MW, 4-MWh Lithium Iron Phosphate ($LiFePO_4$) battery. This is a type of lithium ion battery that uses $LiFePO_4$ as a cathode material. Several battery technologies were compared during the design process. Some of the highly weighted selection criteria included round trip efficiency, cycle life, maximum temperature rating, safety, environmental considerations, and maintenance requirements. Compared with other lithium-ion battery chemistries, the $LiFePO_4$ battery offers improved safety because of the thermal and chemical stability exhibited by the technology. The tradeoff is a slightly lower energy density than other lithium ion chemistries. The specified AC-AC round trip efficiency was 85% while the actual measured AC-AC round trip efficiency was 88%.

The energy stored in the battery can be used either for tariff-based rate arbitrage or power quality and reliability. When grid connected, the battery can charge or discharge as dictated by the Energy Management System in order to maximize the economic benefit of the battery. The rate arbitrage scheme is based on the utility tariff structure and not on real time pricing. During a grid disturbance or outage, the energy in the battery is used to continuously supply high quality power to the on-site loads.

The battery was sized at 2 MW, 2.5 MVA to be able to serve the facility demand, which peaks at 2.8 MW, 2 MVARs in the summer afternoons. This would allow the facility to island from the utility grid when the fuel cell or part of the PV system are on-line, but may require load shedding in the unlikely event that all PV inverters and the fuel cell are off-line.

The 4-MWh storage capacity was sized such that on a typical summer day the battery, fuel cell and solar photovoltaics could serve all of the facility peak-period energy usage. 80% of storage capacity is used for rate arbitrage, reducing the facility peak load. The remaining 20% is reserved for power quality events when the system transitions from grid connected to island operation. This provides enough energy to maintain the system until the diesel generator starts, if required. The battery has an upper and lower state-of-charge limitation of 90% and 10% respectively during grid connected operations to maintain the reserve for power quality. To ensure reliability during island operation a new load and generation management system will control the shedding and adding of load and generation sources (i.e., PV generation or fuel cell) in order to prevent the battery from reaching a full charge or discharge state and shutting down.

B. Power Conversion System

A CERTS-compliant power conversion system (PCS) was required to interface the battery with the Microgrid and utility source. The installed PCS is rated 2 MW, 2.5 MVA, consisting of four DC-to-DC converters that interface with each of the four 500-kW, 1-MWh battery enclosures. Each of the battery enclosures is independent and capable of operating if any or all of the other three containers are shut down. There are two DC-to-AC inverters that interface with two DC-to-DC converters, each through a common DC link bus. This system architecture makes the system highly flexible, allowing for proper maintainability and testing. The PCS was sized such that it could supply some, but not all of the facilities reactive power needs. This is discussed further in the capacitor bank section.

When grid-connected, the EMS dispatches charge or discharge signals to the PCS to provide the highest level of economic benefit to the Jail. To change the rate of power charge or discharge, the PCS responds to "raise speed" or "lower speed" signals, similar to those used in frequency/load control of traditional generation units. The PCS frequency droop curve moves up or down, without changing its slope, thus changing the rate of power charge or discharge of the battery. Similarly the reactive power flow is controlled with the voltage droop curve.

During the transition from grid-connected to island, the PCS remains connected, operating as a voltage source, even if the voltage and/or frequency are outside normal operation limits. The transient recovery voltage period is typically within one cycle, but may last several cycles depending on the circumstances of the islanding process. During this time, the PCS is constrained only by its internal current and power limiting functions.

When the Microgrid is islanded, the CERTS algorithm programmed in the PCS determines the appropriate battery charge and discharge levels within the range established by the frequency and voltage droop curves of the PCS [10].

During passive synchronization with the utility, the PCS is required to remain online even with a wider delta V and Delta F synchronization window than traditionally used.

C. Capacitor Bank

The Jail currently has high reactive power demand due to large rotating loads. This large reactive demand coupled with the on-site renewable sources operating near unity power factor led to a low power factor at the utility point of common coupling. Reactive power compensation would be needed in order to avoid low power factor penalties on utility billing. More importantly, according to a dynamic analysis study, the Microgrid would not be able to island successfully without another reactive power source supplying the rotating equipment. An economic analysis revealed that a capacitor bank was the preferred alternative for supplying the reactive power needs compared to increasing in the PCS MVA rating. A 900-kVAR capacitor bank was installed to provide the remaining reactive power to allow the Microgrid to island.

D. Static Disconnect Switch

A static disconnect switch (SDS) was installed between the utility and Microgrid to allow for very fast islanding and autonomous operation of the Microgrid. There are voltage and current transformers on the line and load sides of the SDS to constantly detect the voltage and frequency of both the utility

TABLE I
PROTECTION SETTINGS FOR THE STATIC DISCONNECT SWITCH.

Protective Function	Device Design Range	Implemented Value
Overvoltage	105 – 115%	115%, 10ms (Fast) 110%, 2ms (Instanteous)
Undervoltage	95 – 80%	80%, 10ms (Fast) 50%, 3ms (Instanteous)
Overfrequency	60.1 – 63 Hz	60.5Hz, 0.5ms
Underfrequency	59.9 – 57 Hz	59.5Hz, 0.5ms
Directional Overcurrent	0 – 500%	130%, 60 sec

and Microgrid systems. These measurements allow the system to island during power failures or power quality events exhibited by the utility. The SDS operates within a quarter cycle on the order of 4 to 10 milliseconds. Disconnection and islanding from the utility are fast enough that any utility events go undetected by the inverter sources in the Microgrid.

The SDS is rated 12.47 kV, 60 HZ, three-phase, with a BIL of 95 kV, for use on a 4–wire solidly grounded system. It has a continuous and load interrupting rating of 300A and an overload rating of 375A (125%) for 120 seconds. The unit thyristor valves have the capability to withstand the surge current of 35 kA for one cycle and 8kA RMS symmetrical for fifteen (15) cycles. It was designed to operate with $\mathrm{N}+2$ redundancy on the thyristor valve devices. This allows the SDS to operate with two thyristor levels shorted out. The overall efficiency is 99% or greater.

The SDS contains islanding and synchronization functions compatible with CERTS protocols. This requires passive synchronization, without the need for external signals for islanding or synchronizing.

Islanding operations are triggered by overvoltage, undervoltage, overfrequency, and underfrequency. There is also directional overcurrent, with current flowing towards the utility grid, required by the utility, programed in the external protective relay that trips the main 12 kV utility breaker. These functions are coordinated with revised overvoltage, undervoltage, overfrequency and underfrequency settings in the fuel cell inverters and PV inverters to ensure that all renewable generation stays online following and islanding transient. The protective setting ranges and implemented values for islanding are listed in Table I.

This SDS was installed in conjunction with bypass and isolation switchgear to allow for servicing of the unit and shutdown in case of any failures.

E. Diesel Generator Upgrade

Santa Rita Jail currently has two 1.2-MW backup diesel generators. These diesel generators would operate only when there was a utility power outage. As part of the Microgrid, the generators are now operated to charge the battery if the battery has a low state of charge when islanded or if the Microgrid fails. This significantly reduces the operation time of the diesel generators… The old speed and voltage controls of the diesel generators were isochronous, meaning they maintained a constant frequency and voltage over any real and reactive power output, within the generators' rated capacity. The controls were modified and upgraded to be CERTS-compliant. CERTS compliant means allowing voltage and frequency droop operation, similar to the operation mode used when operating diesel generators synchronized with the utility grid. Since controllers to operate reciprocating engine-generators synchronized to the utility grid are readily available, off-the-shelf generator control equipment was used for the diesel generator control upgrades, avoiding the need for costly special-design equipment. This is one of the advantages of using CERTS; it simplifies the integration of renewable or large-scale energy storage equipment with conventional generation.

The Santa Rita Jail backup diesel generators are not permitted by air quality regulations to operate when utility power is available. When the microgrid islands due to a utility outage and the diesel generators are called into operation, the generators synchronize with the microgrid and operate in voltage and frequency droop mode (CERTS mode). In this mode of operation, the kW output of the diesel generators are controlled by biasing the frequency droop curve, without changing its slope, until the desired kW output is achieved. Again, this is similar to the strategy used to control kW output of conventional generators when operating synchronized to the utility grid. To minimize the operating hours of diesel generators during a sustained utility outage, the diesel generators are only called into operation when needed; that is when the battery state of charge reaches a minimum island-operation set-point. In addition, when operating in parallel with the microgrid, the kW output of the diesel generators is set to operate close to its rated output, where the operation is most efficient. However, by operating below rated output, there is margin in the output for the diesel generators to share frequency and voltage control functions with the battery per their respective voltage and frequency droop curves. The generators transition back to isochronous control in the event the Microgrid is not operational; that is when the battery is out service. In this case, the system operates just like a traditional backup generation system, the utility power outage would cause a brief power outage in the facility, followed by isochronous operation of the backup diesel generators.

F. Energy Management System

A centralized control system was installed at Santa Rita Jail to optimize the use of the on-site generation sources when grid-connected based on the applicable utility energy rates [11], [12]. This system monitors power flow at various points to determine system loads and available generation. The EMS controls the flow of power across the Point of Common Coupling (PCC). Depending on the actual time-of-use rate (in this project they are peak, partial peak, and off-peak) the EMS will determine its control strategy. For example, during off-peak the system's goal is to charge the battery to a maximum SOC while not setting a new demand peak. The calculation parameters, which are utilized in an algorithm, include predicted average demand load, the available discharge energy from the battery, and the required average charge of the battery. The power flow at the PCC is determined as a function of tariff rate structure, predicted generation profiles, and historical load profiles. Thus the EMS gives the battery extra functionality to reduce operating costs while still maintaining high system integrity and reliability.

G. Systems Studies

Extensive system studies where performed to better understand the dynamic response of the microgrid. A PSLF model of the Santa Rita Jail system, that included the dynamic models of the battery system, the diesel generators and rotating loads, was completed. The PSLF model also included a thyristor-based switch at the PCC (modeled as a switching element able to respond in 10 milliseconds) and elements of the system that do not have a dynamic response to changes in voltage an frequency like the capacitor banks, the fuel cell, the photovoltaic systems, cables, static loads, etc. See Fig. 1. The PSLF model was verified with dynamic response tests performed during the PCS factory acceptance test and during commissioning tests at the Santa Rita Jail site. .

As an example consider the transient when the two diesel generators are introduced to charge the storage system while in island operation. In this case the storage autonomously moves from maximum output of 2 MW to charging while increasing the island's frequency by approximately 1/4 Hz.

The top two plots in Fig. 2 show the real and reactive power for the storage system, the pv, the fuel cell, the capacitor bank and the diesels. The lower two plots are phase-a current and voltage waveforms for the diesels and storage inverter. Before the diesels are introduced the storage is discharging at 2 MW. At $\mathrm{time} = 0$ seconds the generators are connected. Once connected, the power-transition between the battery and the generators occurs over approximately one second. The power oscillations seen here are a result of a non-zero load-angle during synchronization. The inertia of the diesel results in power fluctuations as the power accelerates and decelerates as a function of the position, resulting in a classical second-order response.

The synchronization process is evident from the relative blurring of the voltage waveform prior to $t = 0$ and subsequent alignment of the voltage waveforms after synchronization. The power increase from the gensets and the subsequent reversal of power flow from the storage system is also evident in these figures. These voltage wave forms also demonstrate the robustness of the voltage controller during this event.

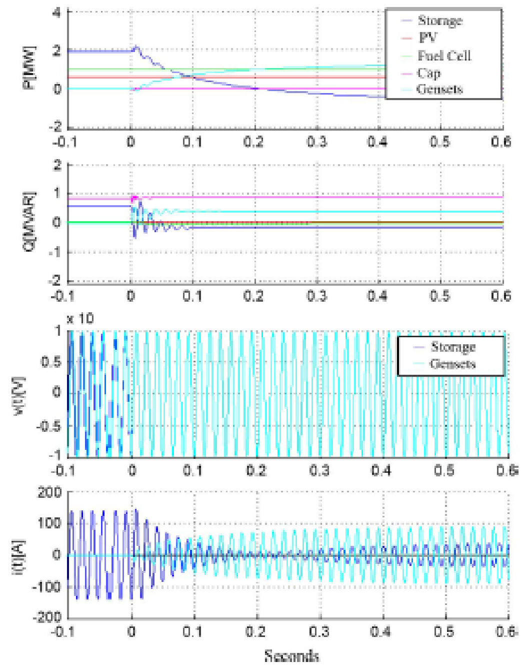

Fig. 2. Simulation of Starting Generators while Islanded.

V. Commissioning Test and Lessons Learned

A. PCS Factory Acceptance Test

To ensure successful commissioning at the site, a complete test of the CERTS functions of the PCS was performed at the factory before shipping. This factory acceptance test included both island and grid-connected operation in CERTS mode. In island operation, the PCS operated alone with a real and reactive power load bank and in parallel with a diesel generator operating in voltage and frequency droop mode. The simplicity of integrating CERTS-capable inverters with other resources operating in voltage and frequency droop was apparent at the factory acceptance test. An off-the-shelf diesel generator was integrated easily with a CERTS-capable inverter. There were no complications other than appropriately setting the droop voltage in the voltage regulator and the droop frequency in the engine governor. During the factory acceptance test, the two sources appropriately shared real and reactive power with no communication lines between the two. The speed at which the PCS adjusts its real and reactive power output on islanding also was verified, within 20 milliseconds for both real and reactive power. The CERTS protocol allows seamless islanding because of the ability of a CERTS-capable inverter to change its real and reactive power output upon sensing frequency and voltage variations at its terminals. Seamless island tests without communication between the utility interconnection breaker and the PCS were demonstrated at the factory acceptance test, even when the PCS was required to change from discharge to charge mode or vice versa (i.e., from positive to negative real power flow).

B. Site Acceptance Test

The system also had to be tested at the site with all of the existing distributed energy resources and the SDS. Once the PCS and the battery enclosures were installed and integrated, island tests of the battery system and the fuel cell with a load bank were completed without including the facility load. However, these tests did not yet include parallel operation of the Santa Rita Jail diesel backup generation system. Once the battery had demonstrated reliable grid-connected operation and island operation with the fuel cell and load bank, a whole-facility island test was scheduled. This whole-facility island test had to be witnessed by Pacific Gas and Electric (PG&E), the local electric utility, as part of the utility's routine pre-parallel inspection process, which any conventional generator has to complete. At that point all of the protective functions required by PG&E were successfully demonstrated and Santa Rita Jail was seamlessly islanded and resynchronized with PG&E for the first time. Only after this had been completed could island operation of the battery, in parallel with the facility diesel backup generation system, be tested. The controls of the diesel backup generation systems had previously been modified to allow voltage and frequency droop operation. The diesel generators with their modified controls were tested and appropriate real and reactive power sharing was demonstrated. This was done at different transient conditions that included battery discharging and charging using diesel generator power.

C. Lessons Learned

Utilities are not yet very familiar with the use of static disconnect switches as a disconnection device at the point of common coupling (PCC). Until SDSs become more common and standards for their use as a PCC disconnection device are developed, conventional equipment must be used to satisfy utility interconnection requirements. In the Santa Rita Jail Microgrid case, a standard 12-kV vacuum breaker and conventional utility-grade protective relays were used upstream from the SDS. Since the SDS operates much faster than conventional equipment in the islanding process (in 8 milliseconds or less), the conventional equipment only operates in the event of SDS failure or when the SDS is out of service and bypassed. In the resynchronization process, after the electric utility restores service, the SDS synchronization function is supervised by a conventional sync-check relay (device 25).

On the battery side, the integration of the battery enclosures and PCS has to be carefully managed. The Battery Management System (BMS) that manages and monitors the condition of the batteries in the battery enclosures needs to communicate with the PCS to report state of charge (SOC), charge and discharge limits, malfunctions, alarms, etc. It may be a challenge to achieve reliable communication in the noisy environment created by fast switching power electronics. Also, accurate SOC reporting is key in a battery system that is charged and discharged daily for rate arbitrage, but also needs to leave energy available for power quality functions.

In a Microgrid system that has so many functions, an overarching control system such as the one employed on this project is an important component. The Energy Management System has different priorities depending on the system operating mode. In grid-connected operation, EMS controls minimize electric power costs while ensuring that enough energy is available in the battery for the power quality functions. In island operation, EMS controls maximize reliability, starting the diesel generators at low SOC and shedding generation as appropriate at high SOC. This is done with the purpose of keeping the battery continuously operating with safe margins in island mode. EMS also has an archive system that records a variety of information, including energy consumption by feeder, real and reactive power flow, power quality monitoring, battery condition, etc. This archive system has proven to be an important tool in improving the system performance. After reviewing archived information, the settings that control grid-connected and island operation were adjusted to improve the benefit the battery provides to the facility. There is still much to be learned about maximizing the benefit that a battery system can provide. The EMS archive system will continue to provide information to support additional improvements.

As was expected, the CERTS protocol simplified the integration of conventional generation equipment with the large-scale energy storage system. This is because the CERTS protocol actually does not require any communications between the large-scale energy storage system and the conventional generation equipment, as long as the large-scale energy storage system follows the CERTS protocol and the conventional generation equipment operates in droop mode. The voltage and the frequency at the terminals of the equipment provide all the communications required for the system to operate and share real and reactive power between conventional generation and the large-scale energy storage system appropriately. This characteristic of the CERTS protocol not only adds simplicity, but also improves reliability. When function beyond simple sharing of real and reactive power are require, like charging or discharging of the large-scale energy storage system at a certain level, at a certain time, these are achieved with simple programming and low speed communication between off-the-shelf designed to control conventional generation that needs to be part of the generation system anyway. This results in lower integration cost and lower communication/control hardware and software cost compared to systems that do not use the CERTS protocol and droop operation, and require sophisticated, high-speed communications among the different elements of the system.

VI. Next Steps

The commissioning test results and system performance monitoring will outline the path forward to further enhancing the CERTS Microgrid operation.

A new load-shedding system will be installed. In Microgrid island mode, the new scheme will have traditional frequency-based shedding. It also will have the ability to control the load and solar photovoltaic, fuel cell, and diesel generation by shedding and adding based on the battery state of charge. In grid-connected mode, the system has the ability to accept an external load curtailment command as a part of a utility demand-side management program.

Future analysis of the battery performance will help in refining operational set points. The current maximum and minimum battery SOC limits used in the grid-connected dispatch algorithm leave a margin of capacity to account for the difference between the predicted and real-time load and generation profiles, plus leave spare capacity to be used in the event of a utility power outage. Refining these values will further optimize battery usage.

The CERTS Microgrid also has the potential to support the grid with ancillary services. The increasingly high penetration of renewable power such as solar photovoltaic and wind put the grid at risk of sudden and unpredictable power fluctuations due to shifts in weather conditions. The Independent System Operator (ISO) is looking for fast-ramping sources such as batteries that can provide frequency regulation to help increase the stability of the grid.

VII. Conclusions

The CERTS protocol has proven to be a powerful tool for integrating distributed energy resources. This first became apparent at the PCS factory acceptance test and later on-site during commissioning and operation of the system. Only minor modifications in the existing diesel backup generation systems were needed to allow it to operate in parallel with the CERTS-capable battery.

Until SDSs are more common and standards are further developed for their use as PCC disconnection devices, conventional equipment like electromechanical breakers and conventional protective relays will continue to be used to satisfy utility interconnection requirements for Microgrids.

Even when CERTS-capable distributed energy resources can operate without necessarily having communication among them, an overarching control system like EMS is necessary to maximize the benefit of a battery system. EMS should include an archive system to provide the information needed to make continued improvements on the system.

The accurate data supplied by the battery management system provides information needed by EMS to adequately manage the battery system. This becomes more important in a battery system that is charged and discharged daily.

To improve the reliability of the Microgrid during island operation, especially at high and low battery state of charge, a load and generation shedding scheme should be considered. It is critical to keeping the battery operating with safe margins and to ensure the reliability of the Microgrid island operation.

Appendix
Equipment Summary

Equipment	Rating	Microgrid Function
Static Disconnect Switch	12.47kV, 300A	Separate from grid upon disturbance
Capacitor Bank	12.47KV, 900KVAR	Provide reactive power during grid connected and island operations
Battery + PCS	Battery – 2MW, 4MWh PCS – 2MW, 2.5MVA	Support transition from grid connected to island; reduce facility peak demand and energy usage
Diesel Generator	(2) 1.2MW	Support island operation when battery is at low state-of-charge
Fuel Cell	1MW	Supply power to facility in grid connected and island operation
Solar PV	1.2MW	Supply power to facility in grid connected and island operation

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Prof. Lasseter is a Fellow of IEEE, and an IEEE Distinguish Lecturer on Distributed Generation.

APPENDIX C:
LBNL: Integration & Operation of a Microgrid at Santa Rita Jail

LBNL-4850E

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

Integration & Operation of a Microgrid at Santa Rita Jail

**Nicholas DeForest, Judy Lai, Michael Stadler,
Gonçalo Mendes, Chris Marnay & Jon Donadee**

**Environmental Energy
Technologies Division**

**presented at the Jeju 2011 Symposium on Microgrids,
Jeju Island, Korea, May 27 - 28, 2011**

http://eetd.lbl.gov/EA/EMP/emp-pubs.html

The work described in this poster was funded by the Office of Electricity Delivery and Energy Reliability's Smart Grids Program in the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Disclaimer

Integration & Operation of a Microgrid at Santa Rita Jail

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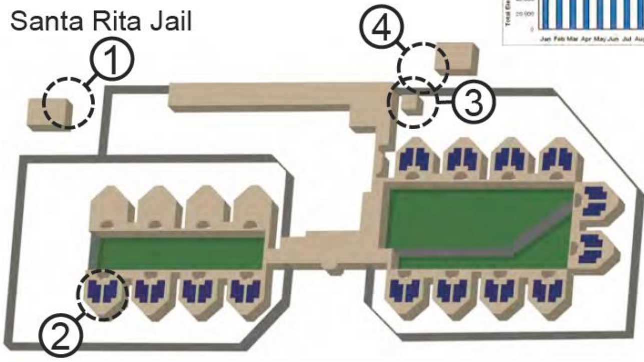
Project Partners: Lawrence Berkeley National Laboratory, Chevron Energy Solutions & Alameda County

Introduction

Santa Rita Jail is a 4,500 inmate facility located in Dublin CA, approximately 40 miles (65 km) east of San Francisco. Over the past decade, a series of Distributed Energy Resources (**DER**) installations and efficiency measures have been undertaken to transform the **3MW** facility into a "Green Jail". These include a **1.2MW** rated rooftop PV system installed in 2002, a **1MW** molten carbonate fuel cell with CHP, and retrofits to lighting and HVAC systems to reduce peak loads. With the upcoming installation of a large-scale battery and fast static disconnect switch, Santa Rita Jail will become a true microgrid, with full **CERTS Microgrid** functionality. Consequently, the jail will be able to seamlessly disconnect from the grid and operate as an island in the event of a disturbance, reconnecting again once the disturbance has dissipated. The extent to which that jail is capable of islanding is principally dependant on the energy capacity of the battery—one focus of this investigation. Also presented here are overviews of the DER currently installed at the jail, as well as the value it provides by offsetting the purchase of electricity under the current Pacific Gas & Electric (PG&E) tariff.

Santa Rita Jail



Tariff Structure

Santa Rita Jail currently purchases its electricity under PG&E's **E-20 tariff**. The tariff (**Table 1**) employs time of use (**TOU**) charges for energy and power demand. TOU rates vary both by month, with "**summer**" and "**winter**" periods, as well as hour of the day, with "**off-peak**", "**part-peak**" and "**max-peak**" periods. There is an additional charge for the maximum monthly power demand. Given the time sensitivity of the E-20 tariff, there is strong incentive to push electricity purchases off-peak. (see Optimization & Scheduling) 2009 monthly electricity bills are given in **Figure 1**, by power and energy charges.

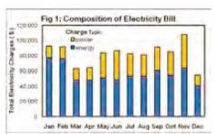


Fig 1: Composition of Electricity Bill

Table 1: Structure of PG&E E-20

Charge Type		power	energy	Duration
Summer	Max Peak	$11.04	$0.14040	12:00-18:00, M-F
	Part-Peak	$2.59	$0.09807	8:30-12:00, 18:00-21:30, M-F
	Off-Peak	-	$0.07992	21:30-8:30, M-F; Weekends
	Maximum	$7.45	-	
Winter	Part-Peak	$0.82	$0.08585	8:30-21:30, M-F
	Off-Peak	-	$0.07664	21:30-8:30, M-F; Weekends
	Maximum	$7.45	-	
		[$/kW]	[$/kWh]	

1 - Microgrid/Macrogrid Connection

Currently, the jail does not have the ability to seamlessly disconnect from the grid in the event of a disturbance. Also, under its current agreement with the utility, it cannot export electricity produced on-site. These conditions have frequently contributed to problems with DER at the jail; sometimes requiring the fuel cell to trip off. Once off, the fuel cell requires several hours to ramp back up to full output. While short, these outages have a potentially significant economic impact by setting monthly power demand charges. Outages are also suspected to have a detrimental effect on the life of the fuel cell stack. By installing a fast static disconnect switch and battery, these issues can be avoided in the future, while also improving reliability at the jail, by way of **CERTS** Microgrid functionality.

2 - PV System

Rated at **1.2MW**, the roof-mounted PV system at Santa Rita Jail has a historic peak generation of only about **700kW**. Of the four PV arrays present at the jail, one has deteriorated significantly, contributing to the low output.

Despite this underwhelming performance, the value of PV is evident in **Figure 2**. Because PV output coincides with peak times, it effectively offsets some purchases of electricity at the most expensive rates.

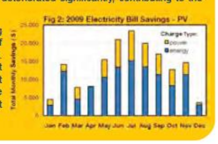


Fig 2: 2009 Electricity Bill Savings - PV

3 - Fuel Cell

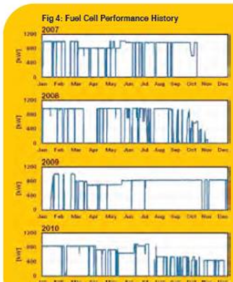


Fig 4: Fuel Cell Performance History

Santa Rita Jail is equipped with a **1MW** molten carbonate fuel cell with CHP. Waste heat from the fuel cell is used to provide approximately **15%** of hot water demand at the facility. The 2009 electricity bill savings from the fuel cell are given in **Figure 3**. Natural gas cost calculations are not presented here. The fuel cell has been plagued by frequent outages—a fact made clear by **Figure 4**. The fuel cell stack required replacement at the end of 2008 and again in 2010. The 2009 cost of outages can be seen in **Figure 5**. Observe that even short outages can have a significant impact on power demand charges. (see **June, November 2009**)

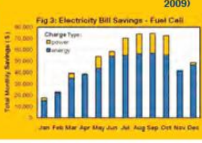


Fig 3: Electricity Bill Savings - Fuel Cell

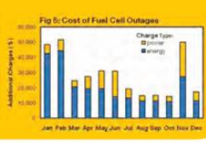


Fig 5: Cost of Fuel Cell Outages

4 - Battery

The installation of a large-scale battery at Santa Rita Jail provides added reliability, plus the potential to shift electricity purchase to less expensive off-peak times. The specifications of the battery will determine the extent to which it can accomplish these tasks. The jail has considered two battery technologies recently, and while this decision is not based entirely on economics, such a comparison has been conducted here to demonstrate how well each fit this specific microgrid application. Assumptions for battery specifications are outlined in **Table 2**.

Table 2: Battery Specifications

Battery		A	B
Technology		Sodium-Sulfur	Li-Iron Phosphate
Energy Capacity	[kWh]	**12,000**	**4,000**
Power	[kW]	2,000	2,000
Roundtrip Efficiency	[-]	0.77	0.83
Decay	[%/hr]	0.002	0.005
Min. SOC	[-]	0.2	0.2

Optimization & Scheduling

The battery is the only truly dispatchable DER at the jail. Utilizing LBNL's Distributed Energy Resources Customer Adoption Model (**DER-CAM**) optimal battery scheduling is determined for several scenario-weeks. This has been conducted for an operational fuel cell (**Scenario 1**) and, more realistically, a short fuel cell outage (**Scenario 2**). The savings as a result of the battery are also tabulated (**Table 3**).

The higher capacity of Battery A allows it to reduce max-peak power demand charges more than Battery B. A is also capable of islanding for longer durations than B, which is of value to microgrid applications. Despite its lower capacity, B still captures a significant portion of potential demand charge savings. B can allow for short periods of islanding. Its installation should also help mitigate disturbance-related fuel cell outages.

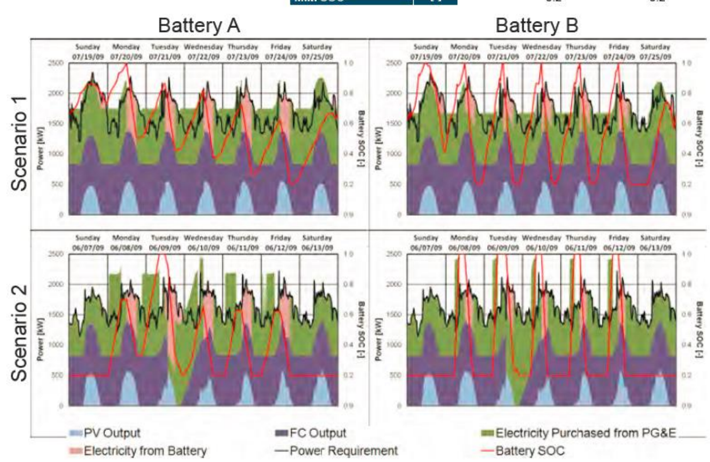


Table 3: Results of DER-CAM Weekly Operations Optimization

Savings from Storage				
Battery			A	B
Scenario	1	energy	$626	$459
		power	$12,586	$9,560
	2	energy	$747	$570
		power	$21,244	$11,363

Note: Power savings assume that monthly demand charges are set during the week investigated.

The work described in this poster was funded by the Office of Electricity Delivery and Energy Reliability's Smart Grids Program in the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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APPENDIX D: University of Wisconsin: Studies on the Santa Rita Jail CERTS Microgrids

2012

UW-Madison, WEMPEC

Robert Lasseter

November 21, 2012

Studies on the Santa Rita Jail CERTS Microgrids

1. Introduction

The Alameda County Santa Rita Jail Microgrid project is a demonstration of Consortium for Electric Reliability Technology Solutions (CERTS) Microgrid concepts. The goal from a research and design perspective is to understand the potential for large commercialization of CERTS Microgrids to future target customers with demand for reliable power. The CERTS concepts include automatic, seamless transitions between grid-connected and island mode of operation with localized control of frequency and voltage stability for individual distributed generation units and have previously been tested and verified in a laboratory setting. The site specific goal of the project included improving system reliability and optimizing the use of onsite generation to reduce energy costs. To demonstrate the CERTS concepts and meet facility goals, the project integrated the existing renewable, clean energy resources (1.2MW solar photovoltaic, 1MW fuel cell) and conventional generation (2x1.2MW diesel generators) with new large scale energy storage (2MW, 4MWh battery) and a static disconnect switch (12 kV, 300 Amps), updated the controls of CERTS-capable generators, and added an overarching control system termed Distributed Energy Resources Management System (DERMS) to economically optimize the use of all generation sources.

The issues addressed in this report are related to the problems resulting from a mixed system. In this case a mixed system implies a mixture of CERTS compliant components such as the storage and the gensets working together with fuel cell and PV sources which cannot contribute to the control of voltage or frequency. Basically in island operation these sources depend on the storage to regulate voltage and frequency in addition to load tracking.

Section 3. explores the transients of the Chevron Microgrid combined system; CERTS storage with the fuel cell and pv solar system. This worked focused on islanding while importing power from the utility. The results indicated that the response of the storage to loss of utility power was fast and well damped. The voltage was well-regulated indication that islanding should have little effect on none CERTS components.

Section 4. explores the use of fixed capacitors to improve power factor at the Santa Rita Jail. The studies focused on system effects of fixed capacitors during islanding transients.

Section 5. explores the issue of synchronous generators droop level within a microgrid system. Grid synchronization of a synchronous-generator-based gen-set has been shown to exhibit frequency and power oscillations under certain circumstances. The following work investigates the conditions under which a 1.2MW generator set will oscillate Microgrid Gen-set Grid

Section 6. the transient stall issues related to gen-sets are investigated. The key point suggest the fast load tracking abilities of inverters seem to be a natural pairing for a gen-set without V/Hz protection which improves response and power quality.

2 CERTS Microgrid Concepts

CERTS Microgrid control is designed to facilitate an intelligent network of autonomous units. The concept has three critical components, the static switch, the micro-sources and loads [2]. The static diconect switch has the ability to autonomously island the microgrid from disturbances such as faults, IEEE 1547 events or power quality events. After islanding, the reconnection of the microgrid is achieved autonomously after the tripping event is no longer present. The re-synchronizing to the utility uses the frequency difference created by the islanding event.

Each CERTS controlled source can seamlessly balance the power on the islanded microgrid using a power vs. frequency droop controller. In this project the large storage system and the backup diesels have the CERTS frequency and voltage control. The fuel cell and the photovoltaic inverters run in a power mode and do not track load, control voltage or frequency of the islanded system. For example if the load increases while in island operation the storage inverter will instantaneously provide the extra power and reduce the operational frequency. At maximum output the frequency controls are designed to drop no more than 1%. If there is inadequate energy to meet the load the frequency will droop below the normal operating range signaling the non- critical loads to shed. The coordination between sources and loads is through frequency.

The voltage controller at the storage inverters and the diesels generators insure voltage stability while islanded. Voltage control must also insure that there are no large circulating reactive currents between sources. This requires a voltage vs. reactive power droop controller so that, as the reactive power generated by the source becomes more capacitive, the local voltage set point is reduced. Conversely, as reactive power becomes more inductive, the voltage set point is increased. At SRJ the droop is held to 5% droop.

The CERTS Microgrid controls do not rely on a "master" controller or source. Each source is connected in a peer-to-peer fashion with a localized control scheme implemented for each component. This arrangement increases the reliability of the system in comparison to having a master-slave or centralized control scheme. In the case of master-slave controller architecture the failure of the master controller could compromise the operation of the whole system. SRJ uses a central communication system to dispatch storage set points, voltage and power as needed to control the state-of-charge. However this communication network is not used for the dynamic operation of the microgrid. This plug and play approach allows for expansion of the microgrid to meet the requirements of the site without extensive re-engineering. Plug-and-play implies that a unit can be placed at any point on the electrical system without re-engineering the controls thereby reducing the chance for engineering errors.

3 Chevron Microgrid Test Sequence Response of combined system of CERTS storage with the Fuel cell and solar.

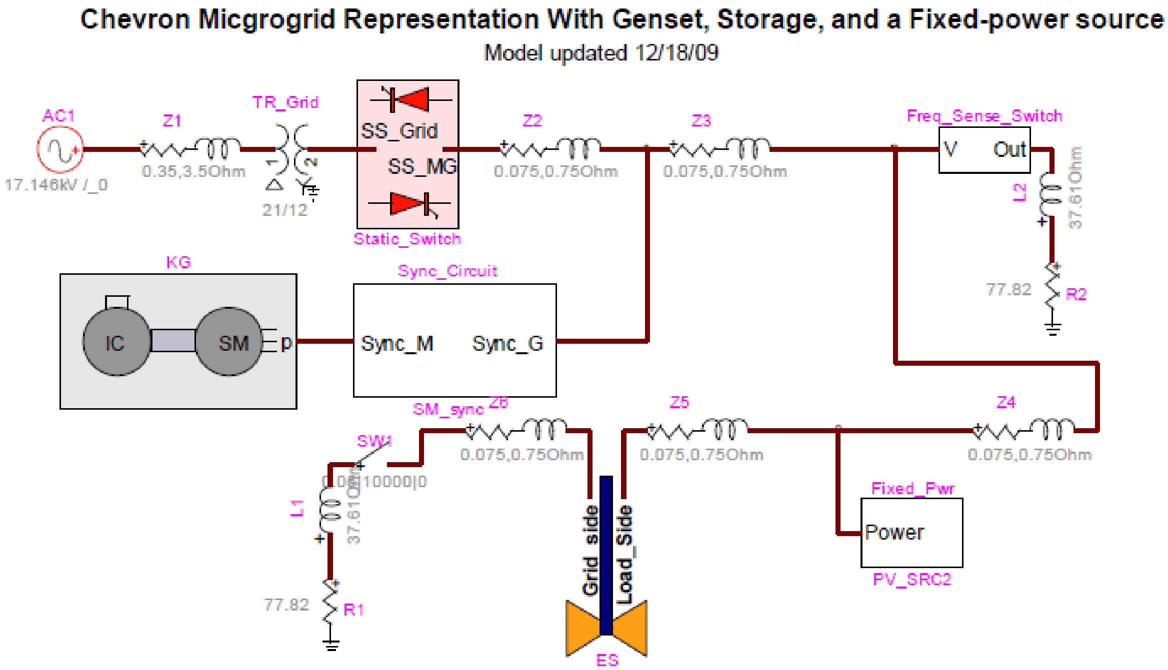


Figure 1 – Chevron Microgrid Model

3.1 *Test 1: Chevron Microgrid Islanding Transient Test*

Conditions: The microgrid configuration was employed as described in figure 1. It utilizes a current-source based fixed-power source* that is used to represent a 1.6MW collection of photo-voltaic and fuel-cell sources. The energy storage element is set to a power output of -0.5MW and for the duration of this test, the diesel gen-set (KG) is kept off-line. At t=0 seconds the static switch is opened and the on-site load, rated at 3MW and 1.4MVAR at nominal voltage and frequency, is supported by on-site generation only.

*It should be noted that an infinitely-stiff fixed-power source causes issues in the simulation world as much as it does in the real world. As these sources act on local information only, current regulation has some delay associated with it as the voltages required to push current can sometimes be unrealistically high in the real world. In the simulations, these voltage spikes can excite a discrete-time resonance which necessitates some finite bandwidth on the power regulation, as will be shown in the following results.

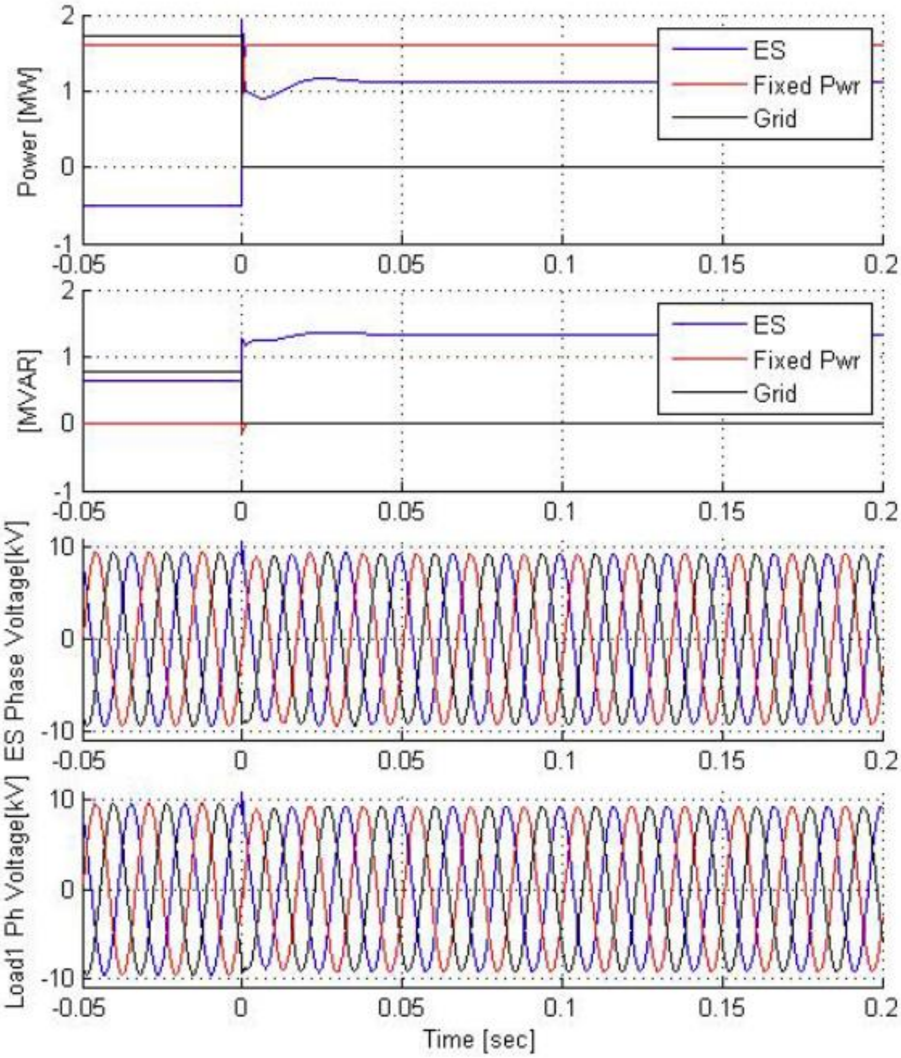


Figure 2 – Composite power, reactive power, and phase-voltage response to island event

Once the island event occurs, the power that originally came from the grid, approximately 1.8MW, is now demanded from on-site sources. The response is fast, well damped, and exhibits a slight reduction in voltage due to reactive power output. The energy storage element immediately increases its power output by approximately 1.3MW, but takes about two fundamental 60Hz cycles for the voltage regulator to adjust to the new operating point to achieve the remaining 0.5MW. Overall, the response is favorable and well damped.

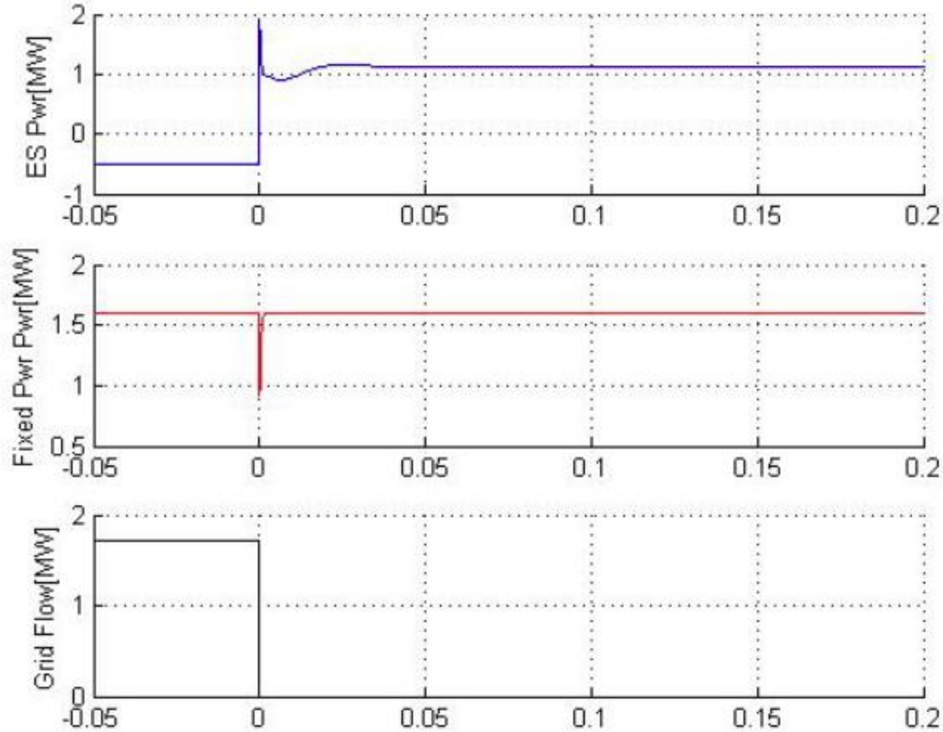


Figure 3 – Power trace break-out for individual characteristic comparison

It can be seen that there is a mild disturbance in output from the fixed-power source, but it returns to the nominal value quickly.

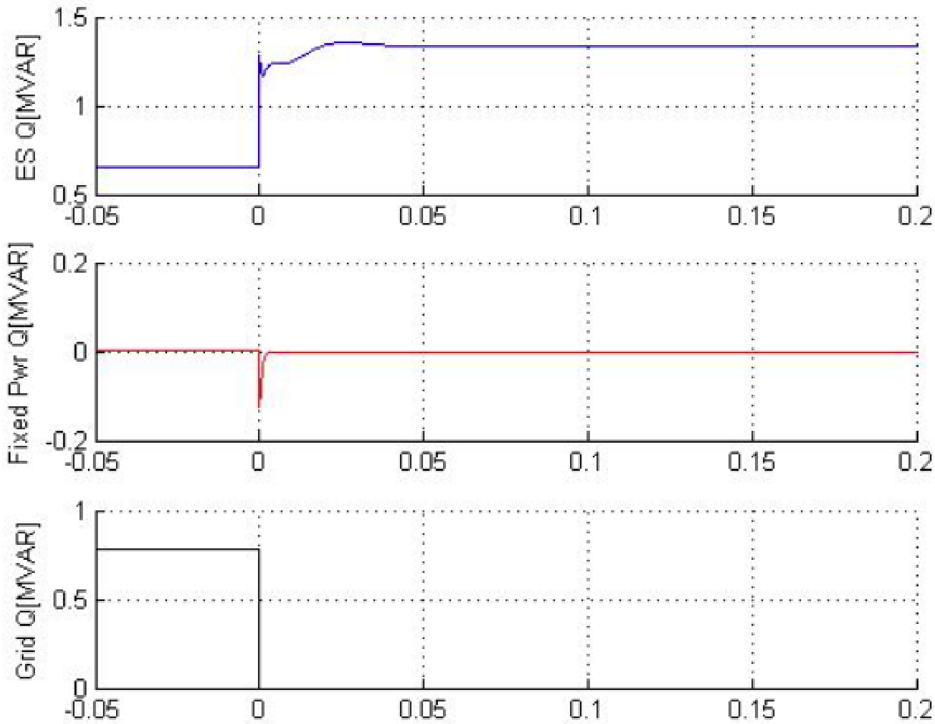


Figure 4 – Reactive power trace break-out for individual characteristic comparison

Following the island event, the energy storage element increases its output of reactive power to support the on-site load. The fixed-power source can be seen to absorb some reactive power for two time samples following the event, but the injected current quickly follows the phase of the new voltage waveform, significantly diminishing the reactive power output.

3.2 Test 2: Chevron Microgrid back-up gen-set connection

Conditions: The microgrid configuration was employed as described in figure 1. This simulation begins in an island configuration with the microsource and the energy storage element online. It the current-source based fixed-power source to represent a 1.6MW collection of photo-voltaic and fuel-cell sources. The energy storage element is set to a 60Hz power set-point of -0.5MW and the diesel gen-set (KG) synchronizer is triggered at t=-0.5 seconds. At t=0 seconds the synchronizer connects the gen-set to the microgrid to alleviate the burden on the energy storage element. The 60-Hz set-point of the generator is set to 0.9pu, or 1.35MW. The on-site load, rated at 3MW and 1.4MVAR at nominal voltage and frequency.

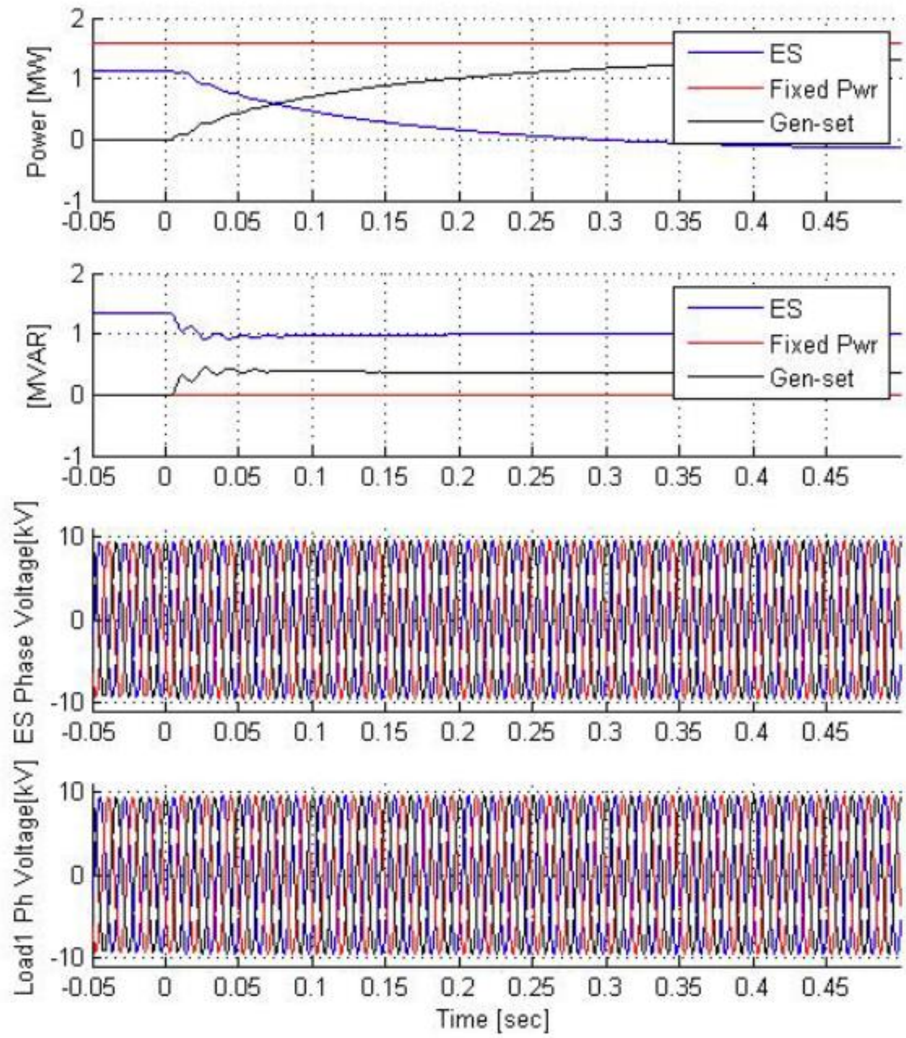


Figure 5 - Composite power, reactive power, and phase-voltage response to back-up generation coming online

Since synchronization occurs when there is little to no phase-angle difference between the gen-set and the point of connection to the microgrid, there is initially similarly small power transfer which allows for smooth engagement of back-up power. As the gen-set increases its power output to establish a steady-state operating point on the microgrid, the fixed-power source remains at the intended power value as it reacts to regulate power given the new operating frequency of the microgrid. Primarily, the gen-set and the energy storage element switch roles in terms of power delivery. There is some disturbance on the power output of the fixed-power source initially, but it is small compared to the total power output and reaches steady-state after three cycles.

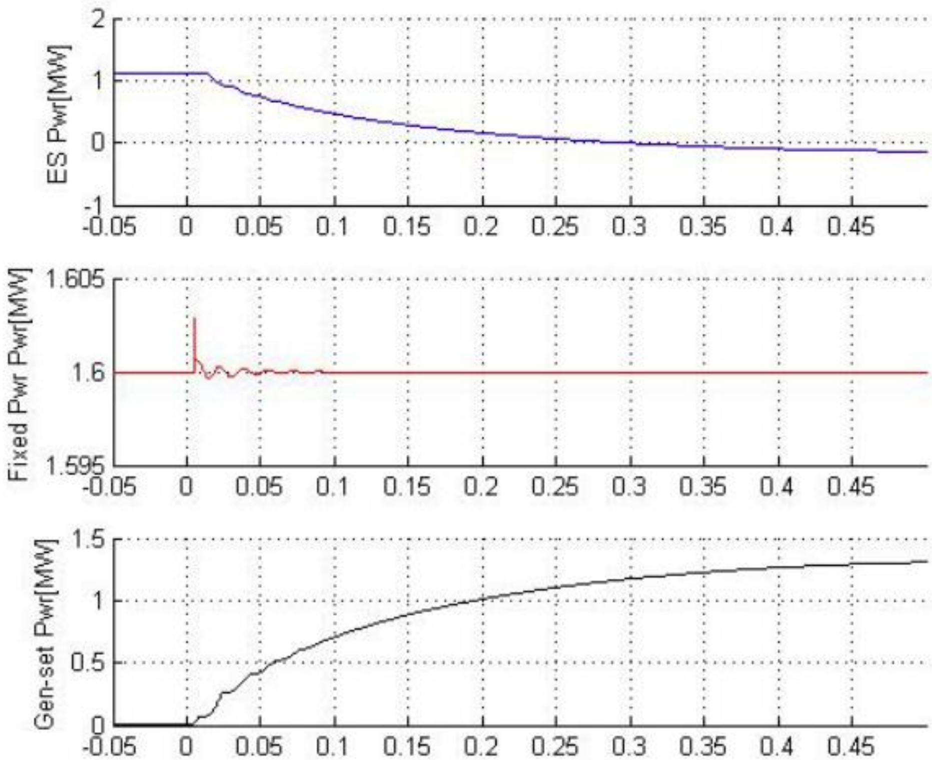


Figure 6 - Power trace break-out for individual characteristic comparison

As previously mentioned, the Gen-set and the energy storage element essentially switch roles, showing mirrored power responses. However, the fixed-power source makes up for the difference between the two characteristics and if there was tighter regulation placed on the output power from the fixed-power source, the traces would mirror each other even more closely, but the fixed-power source is already tuned near the operational limit here considering the network impedances.

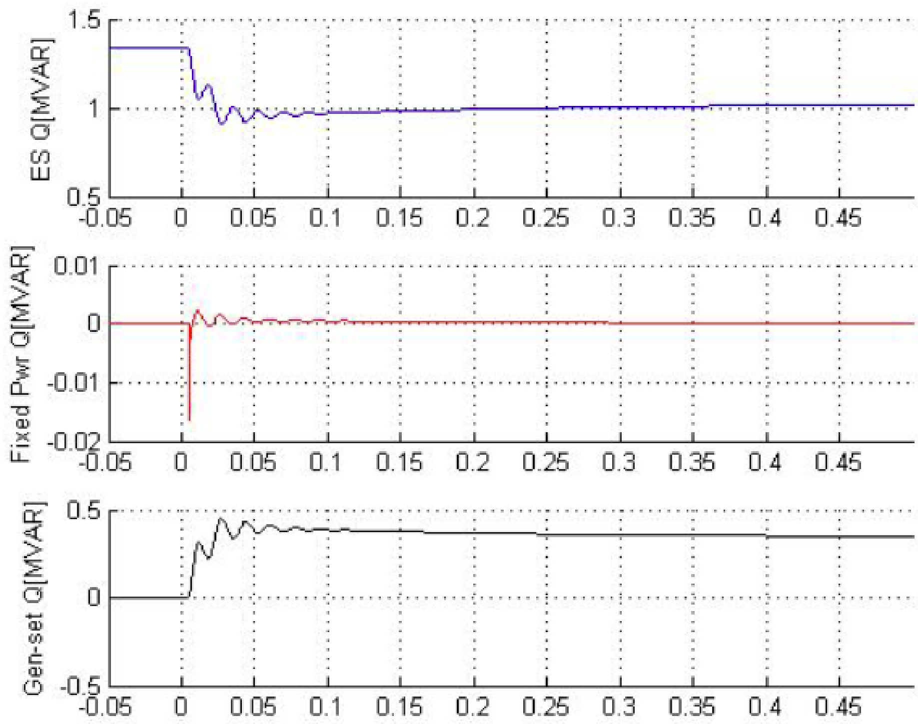


Figure 7 – Reactive power trace break-out for individual characteristic comparison

The damped oscillation in the reactive power response can be traced to the inclusion of a Y-connected RC network to reference the otherwise isolated generator for initialization of the simulation. Similar characteristics could come from the voltage regulator if it was tuned with a bandwidth too close to the settling times of the network elements, but that is not the case here. Without considering the oscillations, the response is relatively well-behaved and does not exhibit large overshoots before steady-state. Also, the values are all reasonable and each provides between 0.42 and 0.88MVAR to support the reactive power requirement of the loads. It is especially that none are negative, reducing the absolute-value total of reactive power required from the sources. The fact that there are un-equal loadings at all can be contributed to the line impedance between the generator and the load that is supplied. Assuming similar cabling throughout, the longer the distance, the more reactive power required to supply power.

3.3 Test 3: Chevron Microgrid Islanding Transient Test, PV only, no fuel-cell

Conditions: The microgrid configuration was employed as described in figure 1. It utilizes the microsource (MS) as the fixed-power source that is used to represent a 0.6MW photo-voltaic source, assuming the fuel-cell source is off-line. The energy storage element is set to a power output of -0.5MW and for the duration of this test, the diesel gen-set (KG) is kept off-line. At t=0 seconds the static switch is opened and the on-site load, rated at 3MW and 1.4MVAR at nominal voltage and frequency, is supported by on-site generation only.

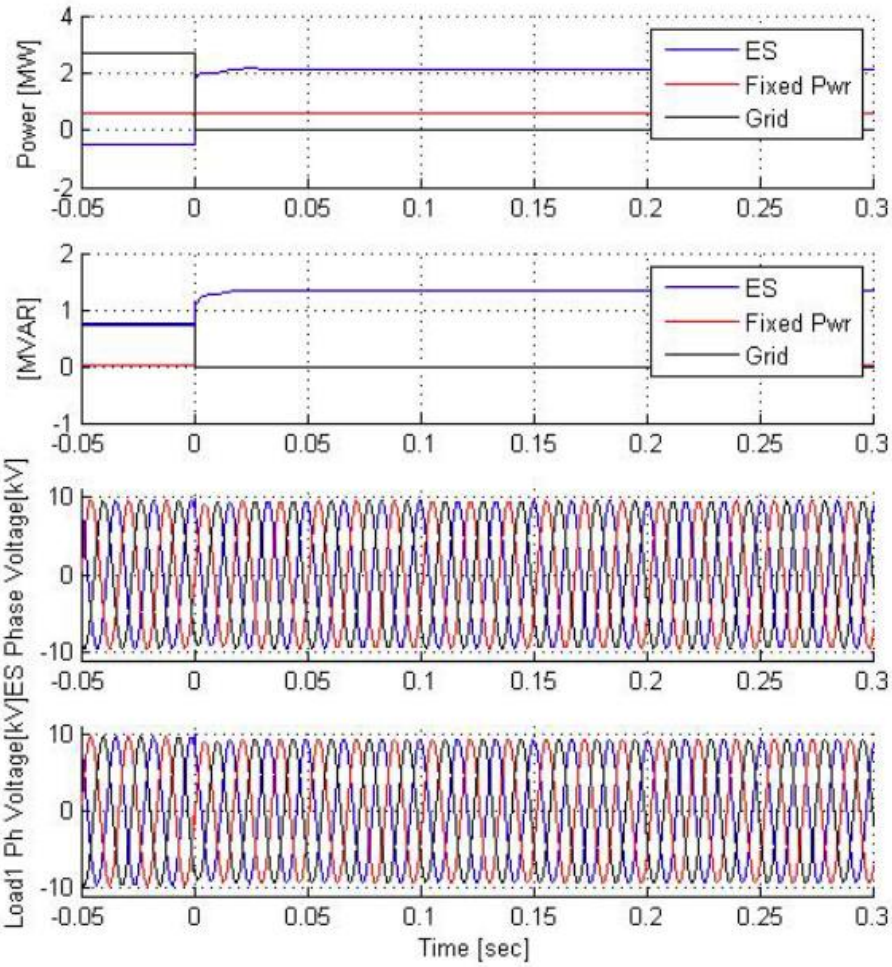


Figure 8 - Composite power, reactive power, and phase-voltage response to island event

The response characteristic here is similar to test 1, figure 2, except that the power output taken up by the energy storage element is 1MW greater, increasing its output to 2.1MW. This reduces the power margin from 1.4MW to 0.4MW, which brings up concerns of voltage and frequency collapse without considering the short-term over-power capabilities of the energy storage element. Again, the voltage characteristic changes only slightly from voltage controller response lag in response to the increased loading from the island transient.

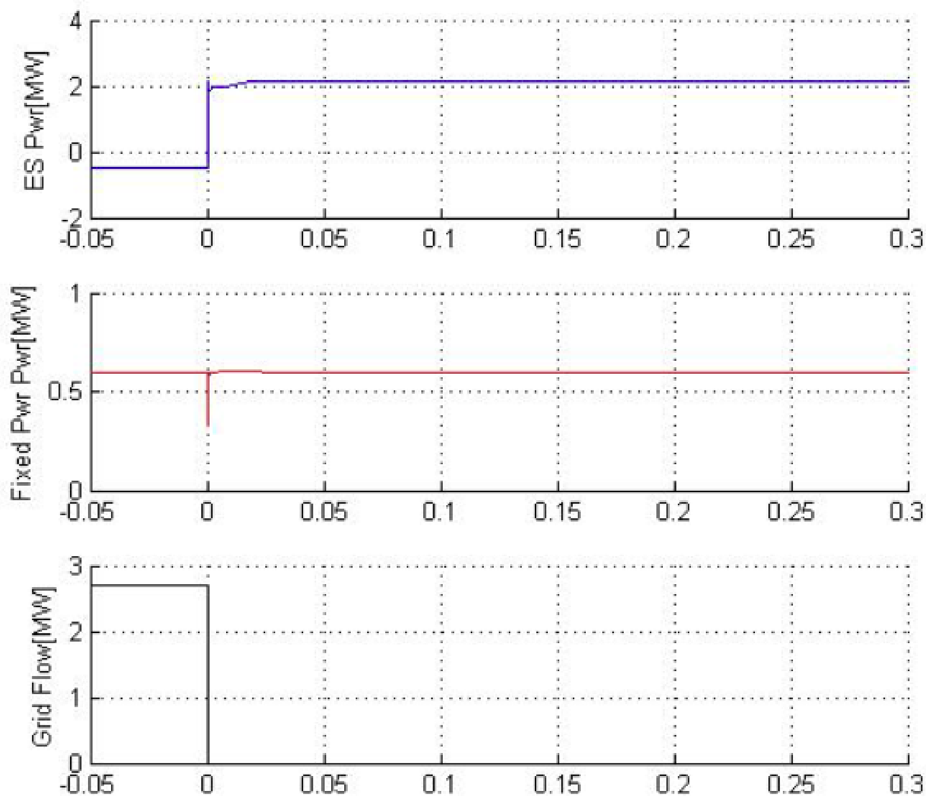


Figure 9 - Power trace break-out for individual characteristic comparison

Here, the power deficit from the energy storage element is small and due in large part to a reduced terminal voltage.

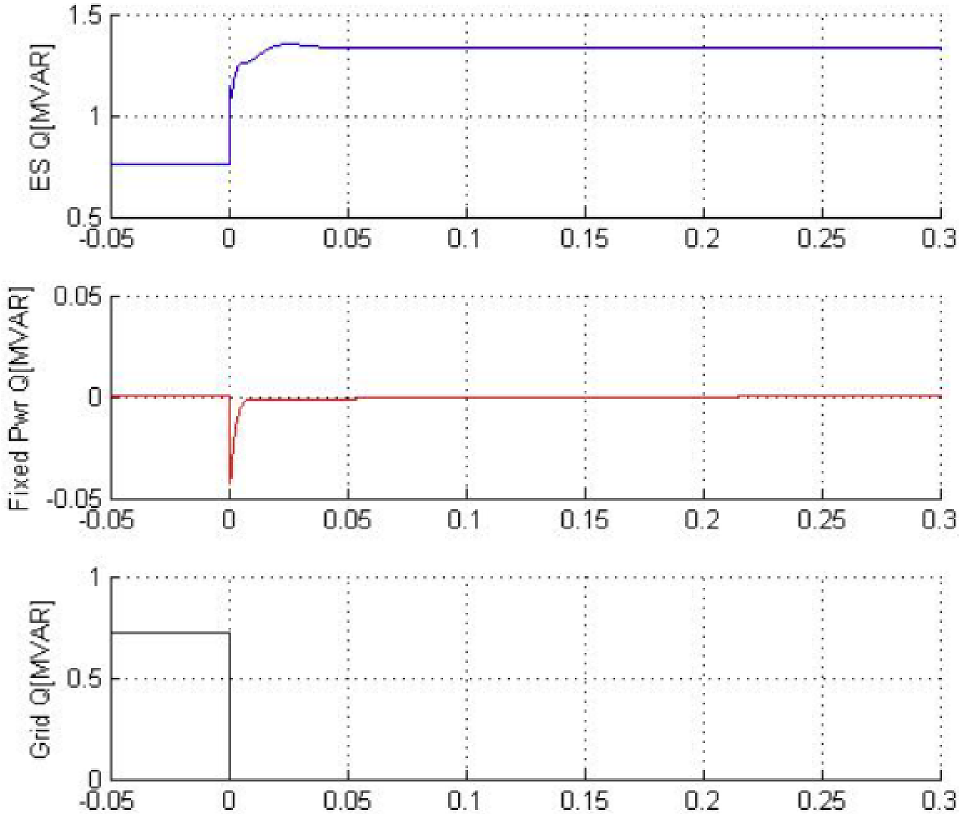


Figure 10 – Reactive power trace break-out for individual characteristic comparison

The reactive power characteristic is nearly identical to that of test 1, but in this case the average reactive power supplied from the energy storage element is greater due to the amount of power it supplies post-transiently.

Appendix A: Modeling assumptions

Lines assumed 4AWG, making 0.375 ohms for the 500 yard length on site. Assuming an x/r ratio of 10, then that means a line reactance of 3.75 ohms. There are five lengths of line, so it is assumed for simplicity that they are equally spaced at 100 yards each.

The synchronous machine has been changed to a power-base of 1.5MW and 8 cylinders. The isolation transformer has been removed, connecting the machine directly to the line (through a synchronizer). The rated voltage has been raised to 12kV as well. The per-unit inertia was kept the same, though with further analysis, it could likely double or triple with the larger machine sizes.

The energy storage unit has been upgraded to a power rating of 3MVA and 2.5MW, maintaining the transformer to keep the DC-bus voltage to 900V, which is within the range of most IGBT switching capabilities. The transformer impedance was corrected to be 0.05pu on either side with an X/R ratio of 2. Also, the battery model was scaled to 200x the original size to achieve the discharge capability of 2.5MW and a charge capability of 0.5MW.

The grid-interface transformer has been sized to 3MVA with 5% impedance on either side. The grid interconnection impedance has been specified as 2.5%, to drop approximately 2.5% of the voltage at 3MVA.

4 Santa Rita Jail Microgrid transient simulations with PF Capacitors

June 2010

Introduction: The Santa Rita Jail power system model was constructed in EMTP (ElectroMagnetic Transients Program) based on a reduced-order model provided by Chevron engineers. This model includes a thyristor-based switch at the entry point of the power system, two diesel gen-sets, a sodium-sulphur (NaS) battery-based inverter, and two fixed-power sources modeled after fuel-cell and photo-voltaic sources. To examine transient power flow characteristics, power meters were used on all lines interfacing with Bus78.

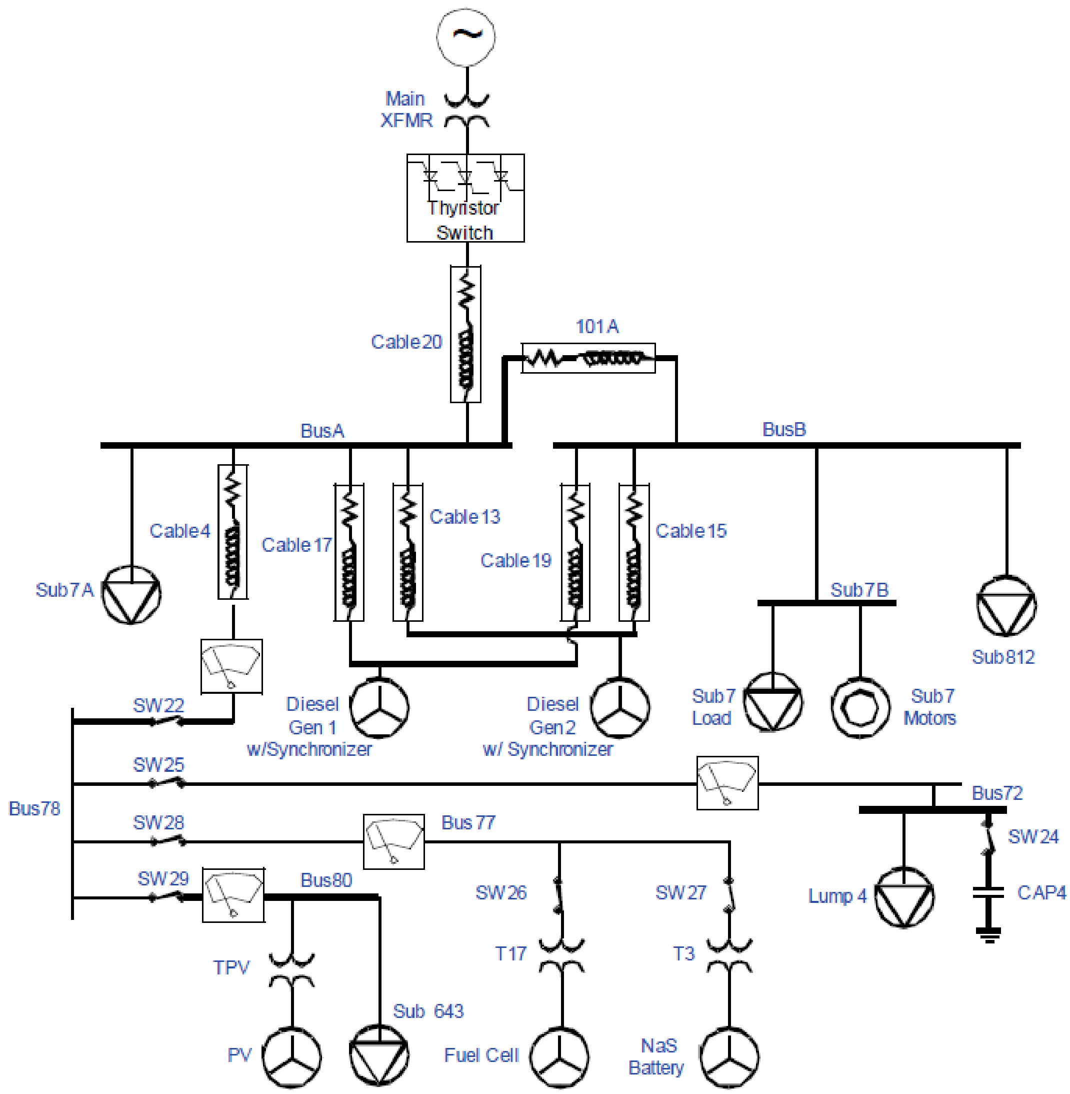


Figure i – 1-line system model used for analysis

Load	Impedance
Sub7A	100+25j
Sub7B	273+169j
Sub7B	(see explanation
Sub812	223+138.4j
Sub643	105+33.7j
Lump4	1440+1080j

Table i – Load impedance summary

Line	Impedance
101A	0.001+0.001j
Cable4	0.084525+0.05082j
Cable13	0.000805+0.000484j
Cable15	0.000805+0.000484j
Cable17	0.000805+0.000484j
Cable19	0.000805+0.000484j
Cable20	0.067072+0.048837j

Table ii – Line impedance summary

Transformer	Impedance
Main	0.441+5.3802j
T3	0.38496+2.7312j
T17	1.8048+13.805j
TPV	1.8048+13.805j

Table iii – Transformer impedance summary

Source and load models:

Impedance loads are modeled as a series resistor and inductor that satisfy the load-flow from the provided load flow analysis from Chevron engineers.

Sub7 Motor load is modeled as a single 125HP induction motor running at 91% of full rated load to match the power draw of the provided load flow analysis. However, the equivalent inertia of the machine was not provided and was assumed to be M=12.

The **NaS Battery source** is modeled after the standard UW incarnation of the CERTS compatible inverter that utilizes a direct-coupled battery to the DC bus. It incorporates both power versus frequency droop and voltage versus reactive power droop algorithms where both the frequency and voltage output are defined by measured quantities of real and reactive power respectively. This source also includes power-limit controllers that limit over-loading situations by following a frequency trajectory outside of the normal operating range of 59.5Hz to 60.5Hz. The existing 5.75% transformer (~7.25mH) is well suited for this frequency range due to the worst-case power change rates without causing oscillatory or under-damped responses. With maximum power flow at 11° of power angle across the inductor, a 1Hz maximum differential will cause a power change of 1.1MW/cycle, which is proportional to the frequency droop range divided by the coupling inductance. This implies that larger droop frequency ranges could be implemented with similar stability characteristics only with a larger coupling inductance but at the risk of forfeiting the assumption of local linearity as the power angle grows to beyond 30°.

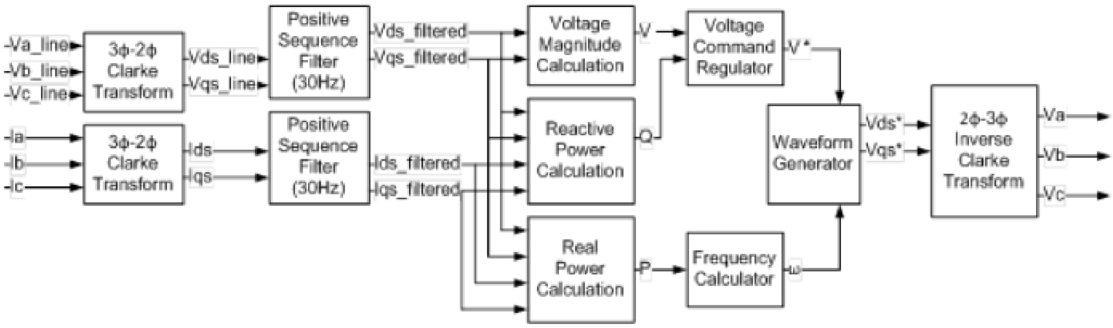


Figure ii – Control block diagram for typical implementation of CERTS compatible voltage-source-inverter

The **fuel-cell and PV** inverter both utilize a current-source based model that injects current in phase with the voltage vector. Later in the testing sequence (transients 3-5), the fuel-cell source utilizes a reactive power input as well as a real power input that injects reactive power based on the difference between the voltage set-point and the measured voltage magnitude. This represents an inversion of the voltage versus reactive power droop employed in the NaS battery source but produces the same result.

Simulation Results:

Presented below are the results from five transient simulations that outline the power from each source and power flows out of bus 72. This implies that power flow out of the bus is positive and the same goes for reactive power where reactive power flows positively from a higher voltage node to a lower voltage node in a reactive network.

4.1 Case 1: Energy Storage (ES) element only, no Fuel Cell (FC), no Photo-Voltaic (PV), no Gen-set. Loads at Sub7a and Sub643 excluded to preserve power balance from ES only operation in island.

Unit	P set-point	V set-	Comments
Grid	-	1.00	Connected until t=0
NaS	-2MW	0.995	
Fuel Cell	-	-	Not Connected
PV	-	-	Not connected
Gensets	-	-	Not connected
Capacitor	-	-	(a) Connected (b) Not connected

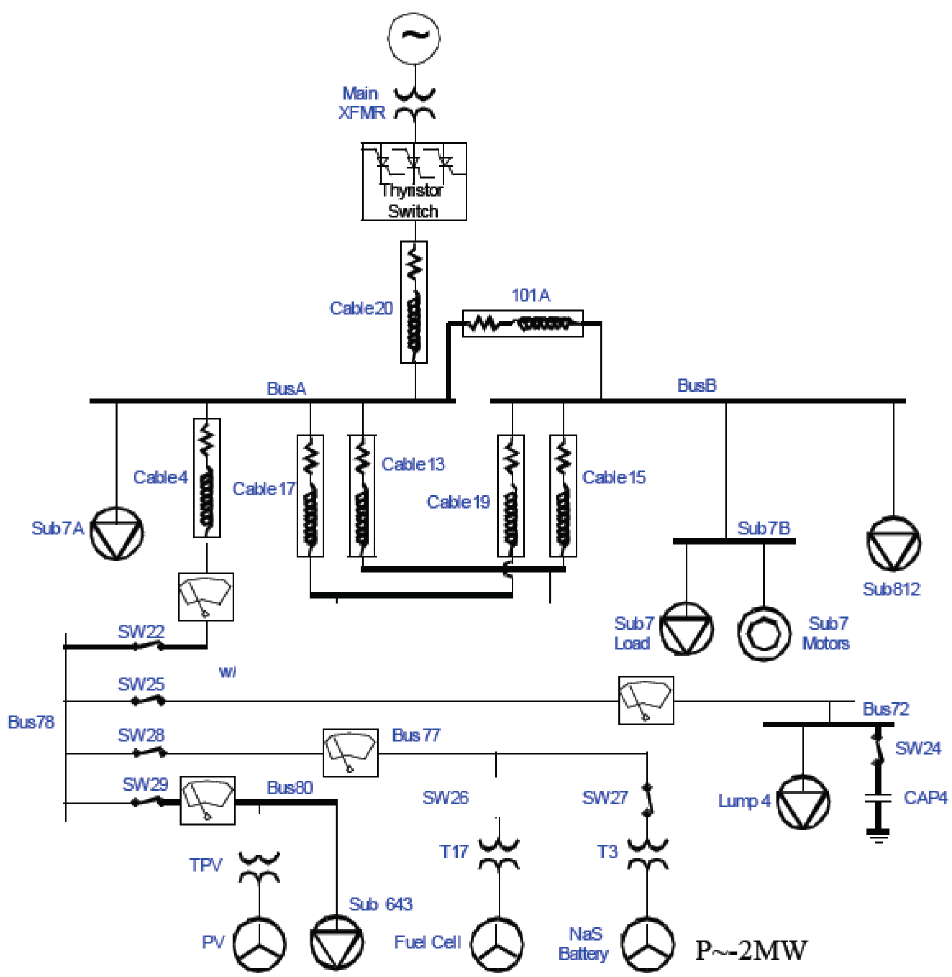
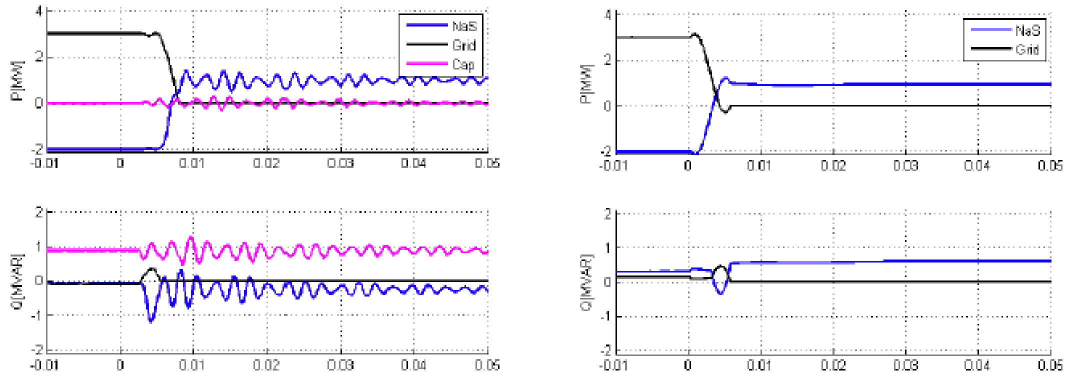


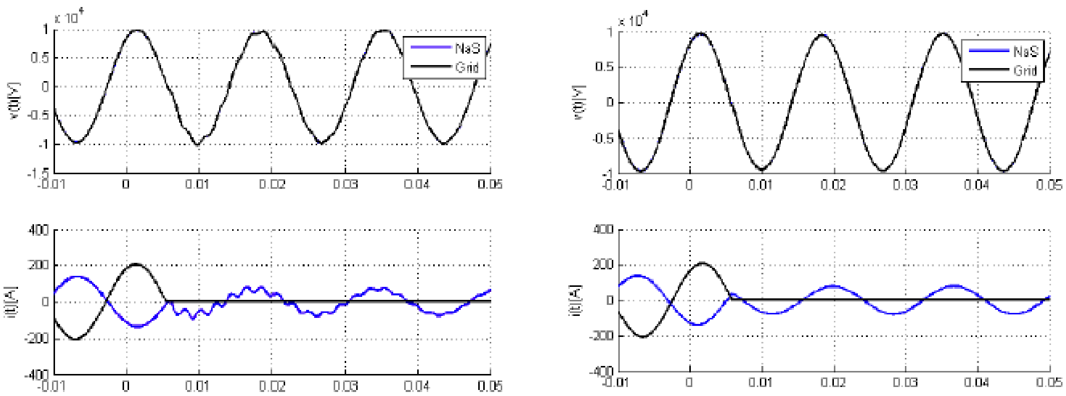
Figure 1 – Santa Rita Microgrid model used for initial island transient simulation. Note the exclusion of fuel-cell and PV model, as well as some load to balance the loss of generation.



With PF Capacitor Without PF Capacitor (C1)

Figure 3 a&b – Power and reactive power after island event at t=0.

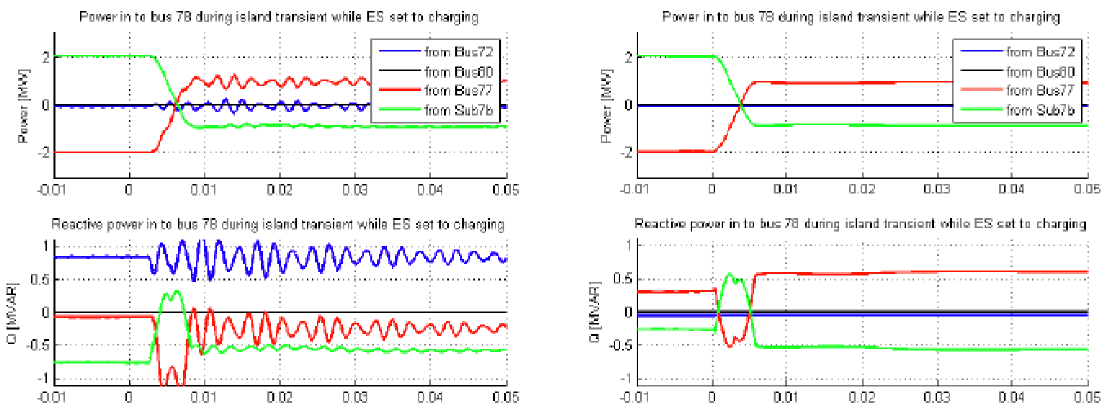
Coincident with a loss in power from the grid tie, the battery goes from a charge state to a discharge state to support the on-site load. Real and reactive power oscillations occur mostly due to the presence of a power-factor correcting capacitor. In the reactive power section of figure 3, the oscillations can be seen as nearly equal and opposite in phase, which is expected due to conservation of reactive power.



With PF Capacitor Without PF Capacitor (C1)

Figure 4 a&b – Voltage and current waveforms following an island transient at t=0.

Some waveform distortion in voltage and current can be seen following the zero-crossing of current at the static switch. These oscillations damp out almost entirely in the 50ms of the plotted trace.



With PF Capacitor　　　　　　　　Without PF Capacitor (C1)

Figure 5 a&b – Load flows in to Bus 78 of Santa Rita model

Figure 5 shows load flows into bus 78 from other busses in the network. These measurement nodes can be seen in figure 1 represented as dial gauges and in figure 2 on the right side. As expected, all traces add to zero for both reactive and real power. The primary change visible in the traces is the re-distribution of power flow from bus 7b and then from bus 77 after the transient. Reactive and real power oscillations are visible in figure 5a between busses 72 and 77. Bus 72 houses the capacitor and bus 77 houses the battery that is used to support the islanded network, so it makes sense that oscillations would occur between these two busses as the other busses are entirely passive loads.

Fixed-capacitor resonant frequency:

The main resonant circuit is defined between the fixed capacitor (C1) and the transformer inductance on the NaS battery. With an inductance of 7.2mH and a capacitance of 16.28uF, the LC resonant circuit equation can be used:

$\omega=1/\mathrm{sqrt}(L*C)= 2922\text{rad/s},\ f=\omega/(2*\mathrm{pi}) = 463\text{Hz}$

From the graph, 6.5 cycles can be counted in 19.5ms, equating to 448Hz. If the resistance is factored in to calculate the damping ratio, a reduced oscillatory frequency can be defined as follows,

$\alpha=R/(2L)= 0.385/(2*0.0072447)=26.6$ [nepers/sec]

$\zeta=\alpha/\omega=26.6/2922=0.00912$,

This damping ratio is small enough to neglect as it represents a very lightly damped condition with a time constant of:

$\tau= 1/\alpha = 1/26.6 = 37.6\text{ms}$

which is a number that appears consistent with figure 3a where after 37.6ms, the harmonic oscillations have decresed to approximately 32% of their original value.

For completeness, the damped oscillatory frequency is calculated to be:

$\omega\_damped = \omega*sqrt(1-\zeta^2) = 2921$

which does not vary significantly from the natural frequency.

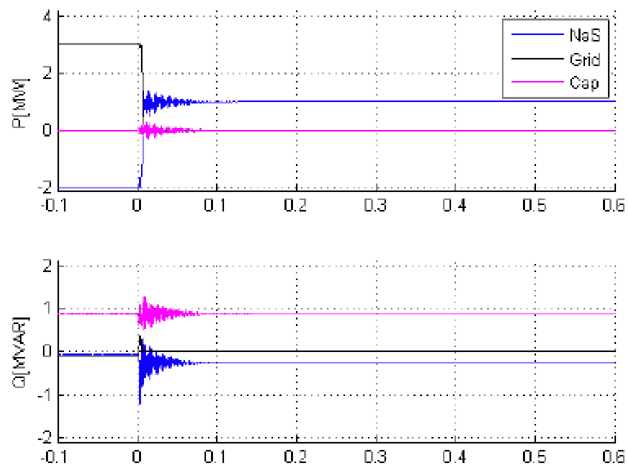


Figure 6 – Same as figure 3 on a -0.1 to 0.6 second time scale

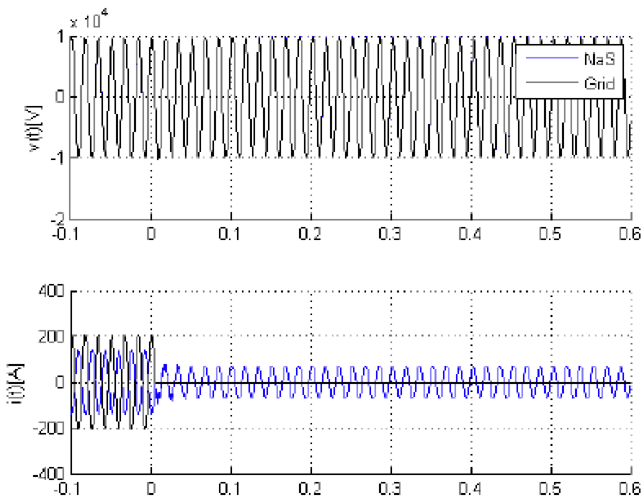


Figure 7 – Same as figure 4 on a -0.1 to 0.6 second time scale

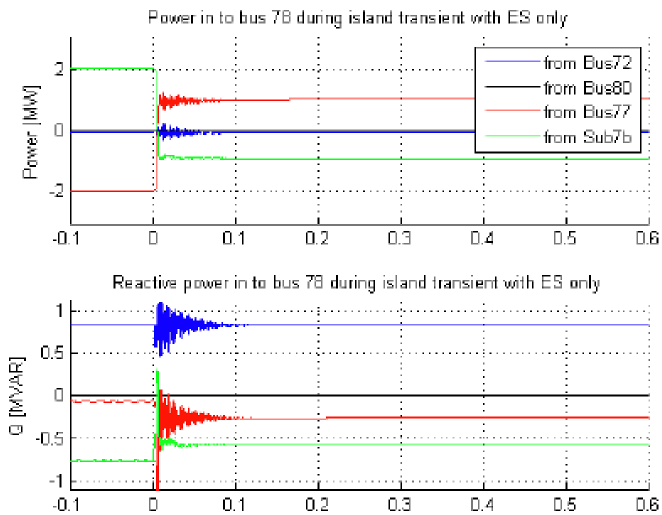
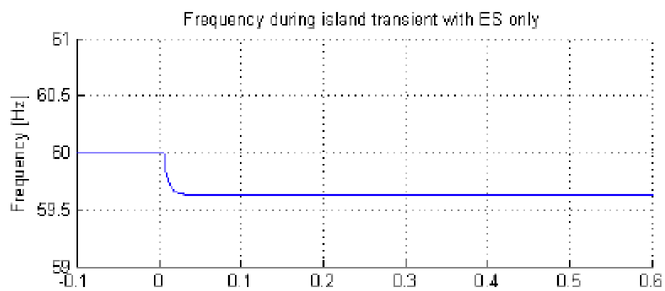


Figure 8 – Same as figure 5 on a -0.1 to 0.6 second time scale



Figures 9 – Island transient frequency characteristic on a -0.1 to 0.6second time scale.

4.2 *Island transient 2: Energy Storage (ES) element, Fuel Cell (FC), Photo-Voltaic (PV), no Gen-set. All loads included.*

Unit	P set-point	V set-	Comments
Grid	-	1.00	Connected until t=0
NaS	-2MW	0.995	
Fuel Cell	1MW	-	Unity power-factor
PV	0.6MW	-	Unity power-factor
Gensets	-	-	Not connected
Capacitor	-	-	Connected

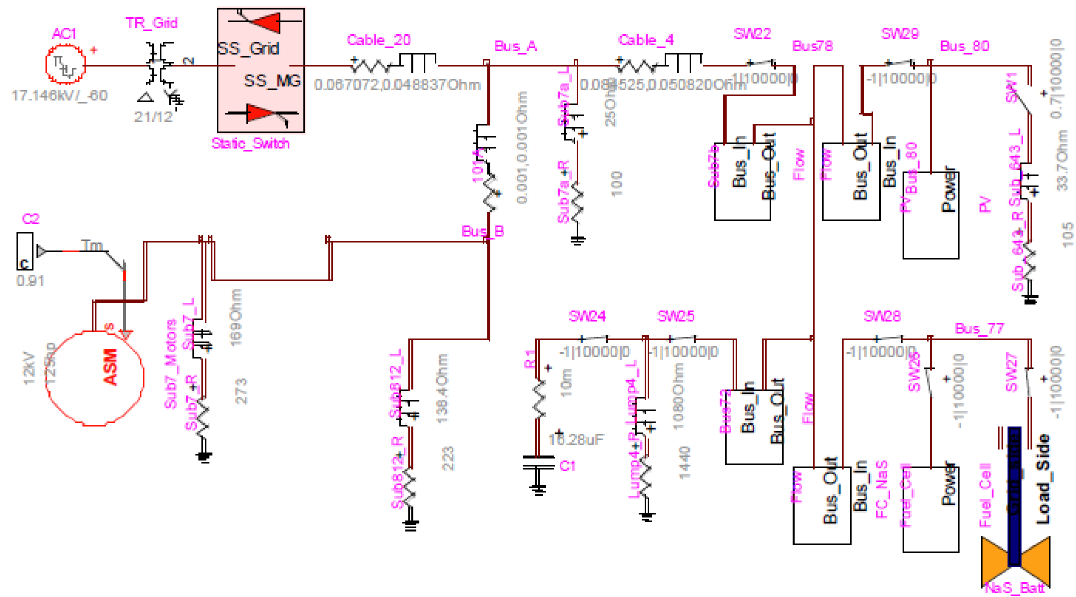


Figure 10 - Santa Rita Microgrid model used for second island transient simulation. Note the inclusion of fuel-cell and PV model.

In this island event, the fuel-cell and the photo-voltaic inverter models are included. They are unity power factor sources prior to their isolation transformers. These sources are commanded to operate at a fixed output power to simulate unvarying utilization of their respective resources.

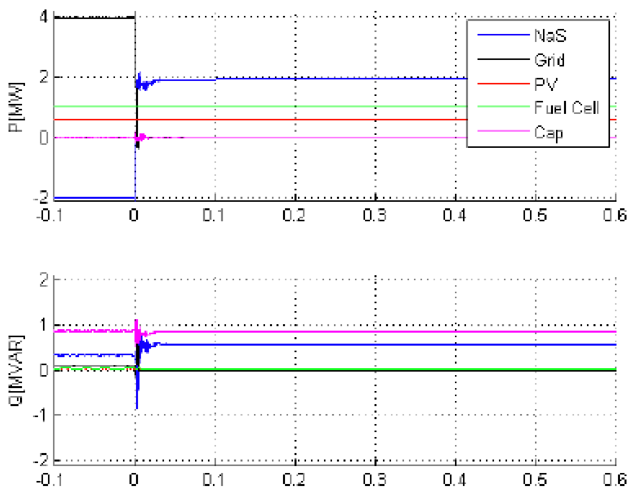
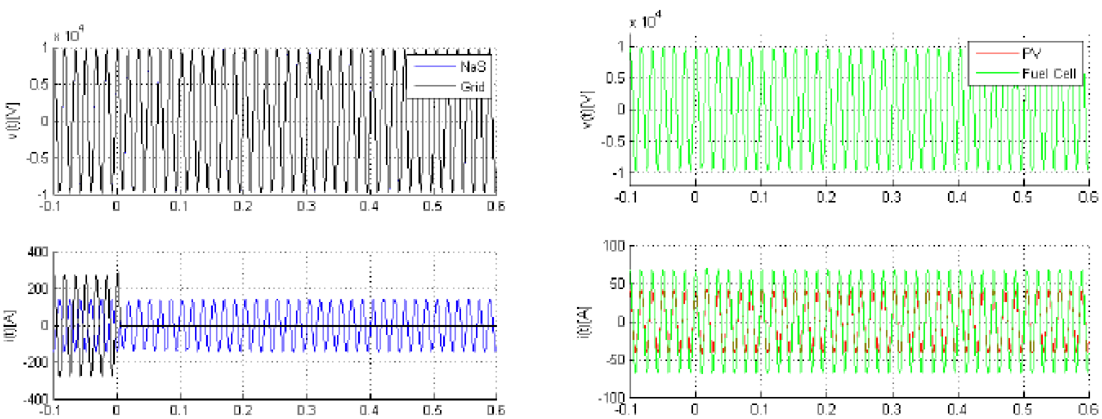


Figure 11 – Power and reactive power after island event at t=0.

Similar to figure 2, the power defficit from the grid-tie is covered by the battery. Some power and reactive power oscillations can be seen, but it damps out quicker than as seen previously which is primarly due to the addition of the fuel-cell and PV sources, as well as the inclusion of the loads at Sub_7a and Sub_643. The inclusion of these loads decreases the time constant to 2.6ms, reducing the oscillations to a inpercievable amount after three time constants (7.9ms) which is consistent with all traces presented in the present case.



a) NaS battery and Grid flow

b) PV and Fuel Cell sources

Figure 12 - Voltage and current waveforms following an island transient at t=0.

Similar to figure 3, the voltage and current waveforms exhibit some damped oscillations immediately following the island event. Consistent with figure 11, the oscillations are much reduced as compared to the initial island transient without the unity power-factor sources.

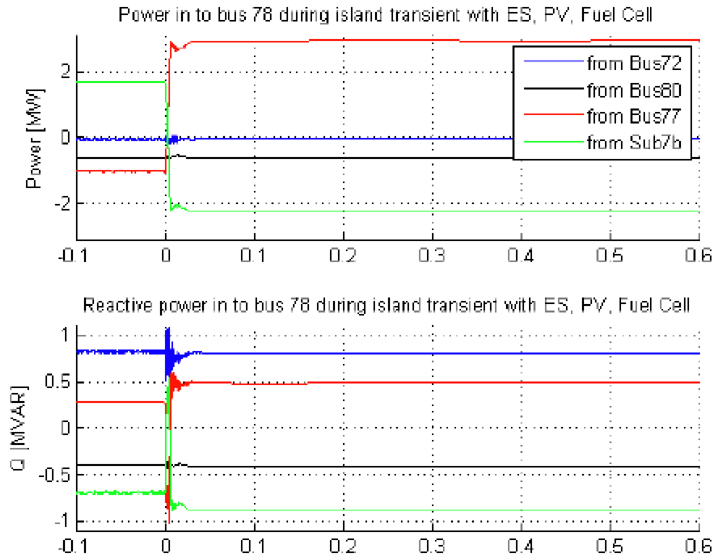


Figure 13 - Load flows in to Bus 78 of Santa Rita model

Load flows shown here in figure 13 exhibit much of the same characteristics as the the previous transient. The reactive power change during the thyristor free-wheeling immediately following the island event is quite noticable and due to un-equal loading of phases once one phase has disconnected and the other two have yet to discontinue their conduction.

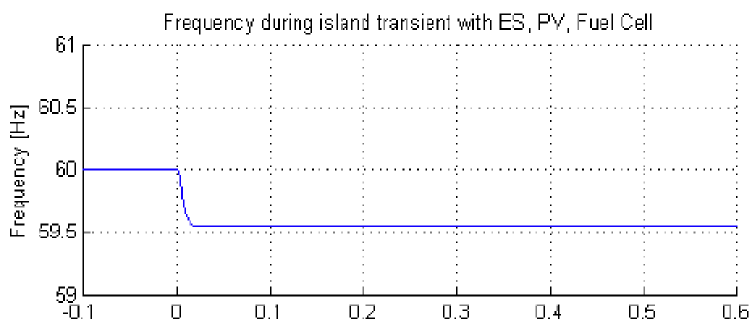


Figure 14 - Energy storage inverter frequency following island event.

4.3 Island transient 3: Energy Storage (ES) element, Fuel Cell (FC) with reactive power droop, Photo-Voltaic (PV), no Gen-set. All loads included.

Unit	P set-point	V set-	Comments
Grid	-	1.00	Connected until t=0
NaS	-2MW	0.995	
Fuel Cell	1MW	1.01	Uses Q vs. V droop

PV	0.6MW	-	Unity power-factor
Gensets	-	-	Not connected
Capacitor	-	-	Connected

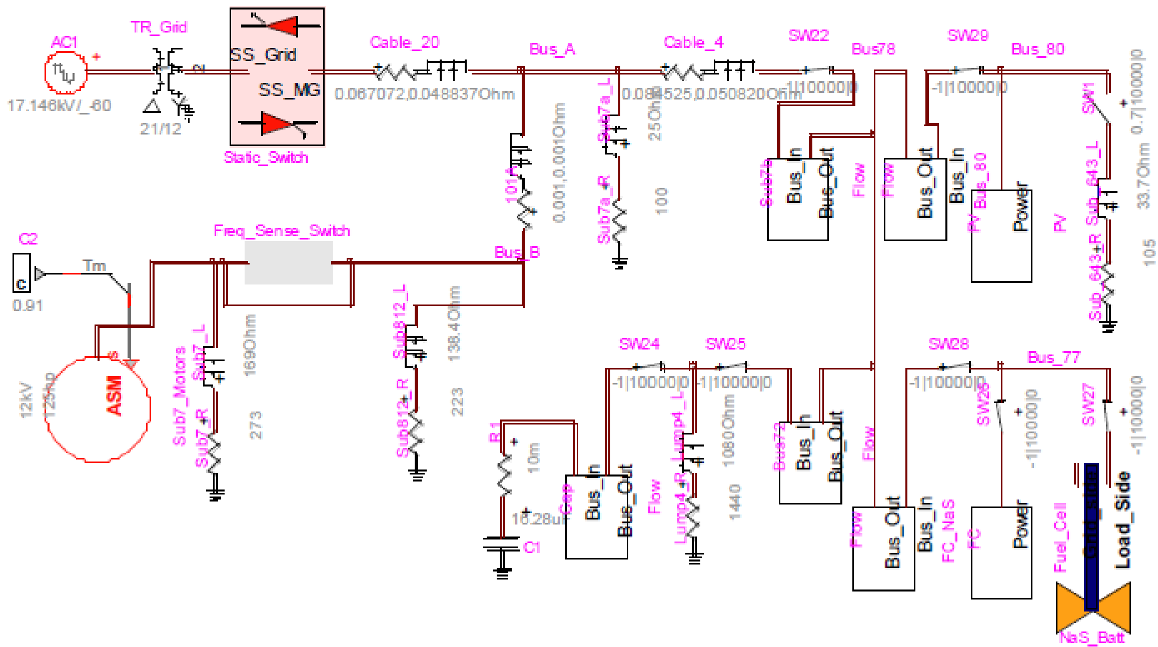


Figure 15 - Santa Rita Microgrid model used for third island transient simulation. For this test, the fuel-cell source has been modified to change its reactive power with respect to the measured terminal voltage.

The reactive power voltage droop method employed in the fuel-cell is slightly different than the NaS battery as the battery will measure the reactive power and change its voltage, but the net effect is the same. It is because the fuel-cell inverter is current-source based that this method is more easily applied.

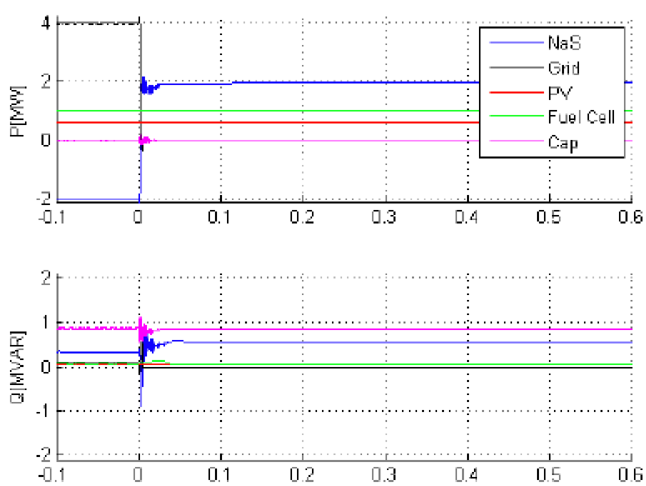


Figure 16 – Power and reactive power following island transient

For the most part, there is little difference between the previous island event and the current one except for the slight variation in reactive power from the fuel cell source in the second plot of figure 10. Little reactive power change is visible as the voltage did not vary significantly. In this case, the fuel-cell model utilized a 1pu (1MVAR) output for a 5% voltage droop, but only a fraction of a percentage was percieved by the local voltage magnitude measurements. Otherwise, the characteristic is quite similar.

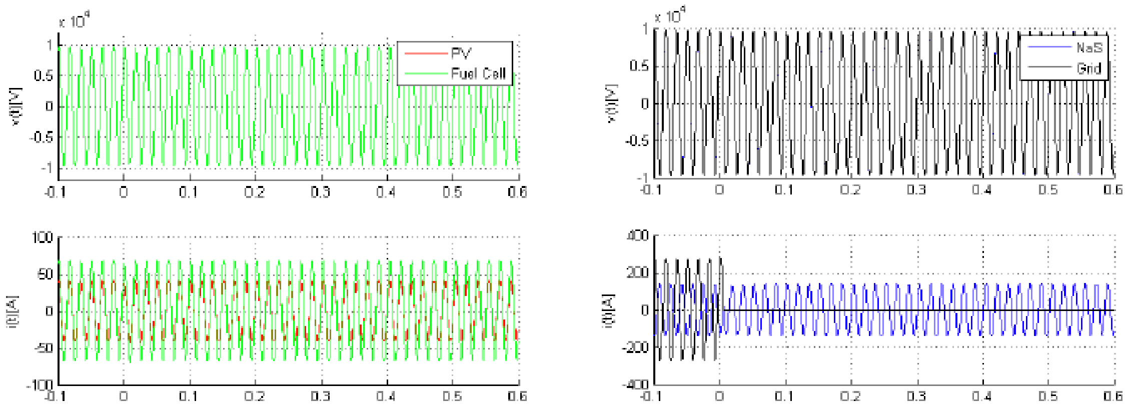


Figure 17 – Voltage and current trances from island transient with reactive power voltage droop.

The trace in figure 17 doesn't differ much from the analog in figure 7, but a rather general conclusion can be drawn that reactive power support does not appear to destabilize or otherwise adversely affect the transient response of a microgrid event. In fact, the oscillations appear even more damped following the transient which makes a solid case for at least a hybrid of fixed capacitors and statcom-type reactive power support that has been added into the fuel-cell inveter.

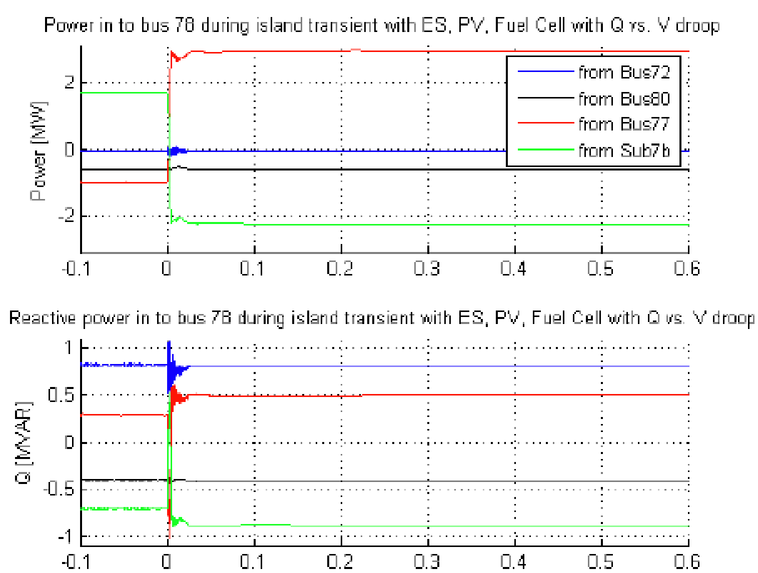


Figure 18 – Power flows from bus 78.

Consistent with the other plots from this transient, these traces bare resemblence to the second transient, exhibiting similar harmonic oscillations in magnitude and persistance.

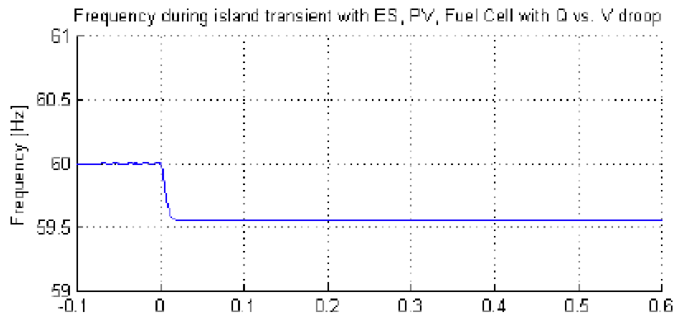


Figure 19 - Energy storage inverter frequency following island event

4.4 Island transient 4: Energy Storage (ES) element, Fuel Cell (FC) with reactive power droop, Photo-Voltaic (PV), no Gen-set, no capacitor. All loads included.

Unit	P set-point	V set-	Comments
Grid	-	1.00	Connected until t=0
NaS	-2MW	0.995	
Fuel Cell	1MW	1.10	Uses Q vs. V droop
PV	0.6MW	-	Unity power-factor
Gensets	-	-	Not connected
Capacitor	-	-	Not connected

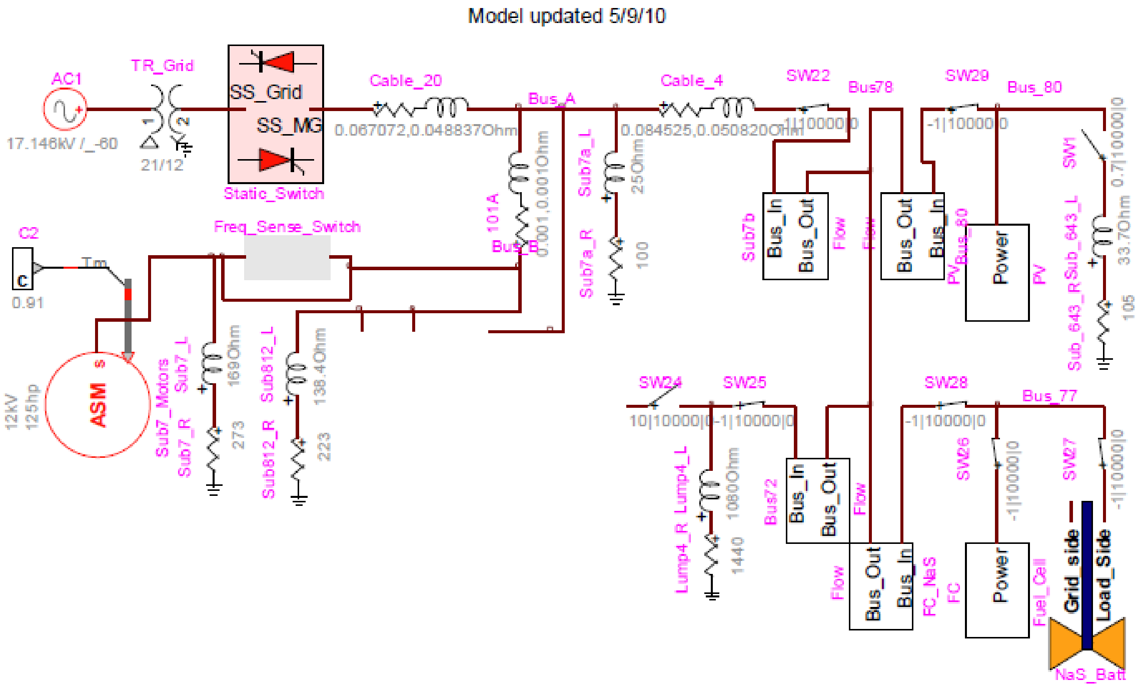


Figure 20 - Santa Rita Microgrid model used for third island transient simulation. For this test, the fuel-cell voltage setpoint has been modified to compensate for the removal of the fixed capacitor.

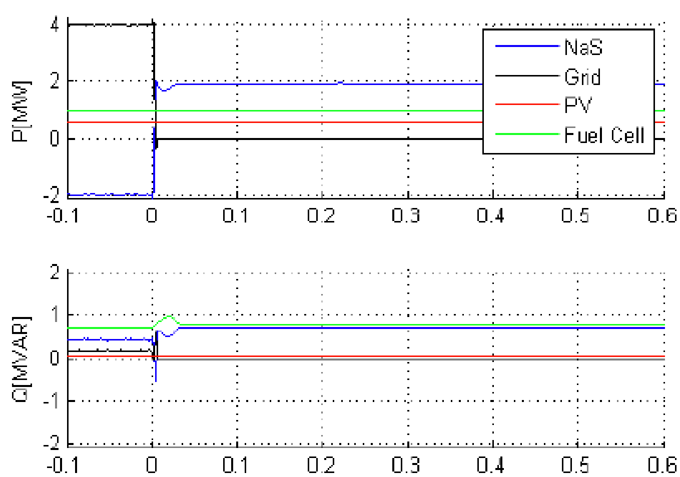


Figure 21 – Power and reactive power following island transient

As can be seen on figure 21, the reactive power from the fuel cell is significant whereas the reactive power from the grid supply is only a small fraction of the local reactive loading. In this case, the total current from the fuel cell current peaks at 75-80A/phase versus the previous case with the fixed capacitor that required 65-70A/phase. In round figures, this additional requirement represents a 15% increase in inverter rating to provide local reactive power support without undesired LC resonance that comes from the fixed capacitor.

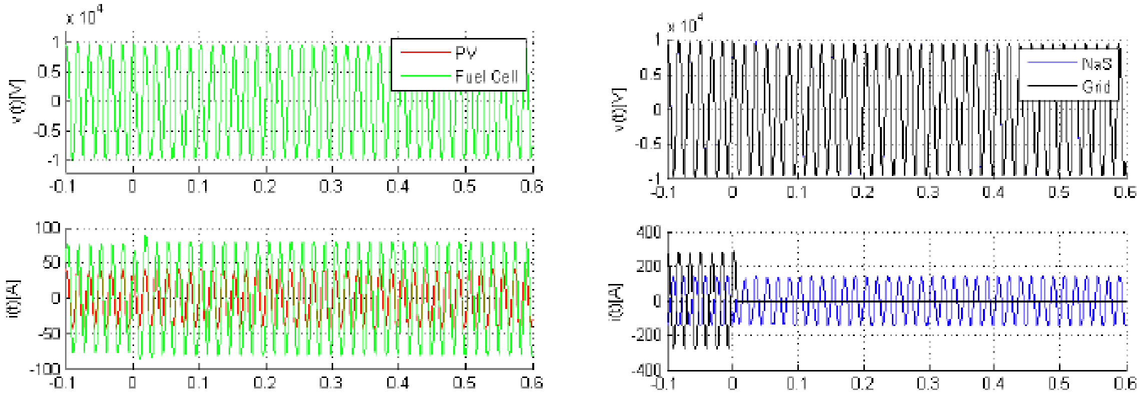


Figure 22 – Voltage and current trances from island transient with reactive power voltage droop.

Figure 22 looks similar to previous power traces except for the increase in current magnitude from the fuel-cell.

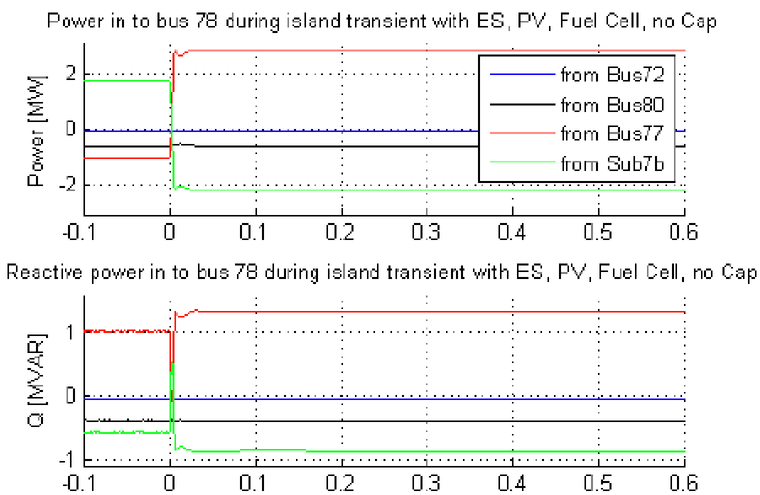


Figure 23 – Power flows from bus 78.

One main change in power flows in this case is the reduction in damped oscillatory dynamics which is expected from the removal of the fixed capacitor. As the fixed capacitor represented the only significant capacitance in the network, its removal results in a significant change in the oscillatory network dynamics.

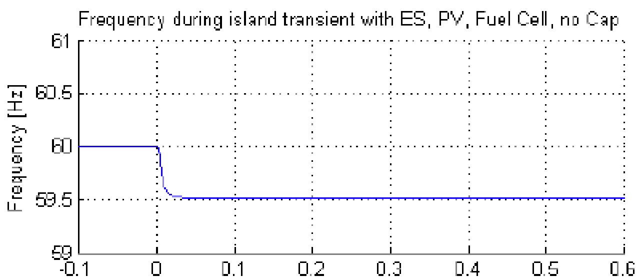


Figure 24 - Energy storage inverter frequency following island event.

4.5 Transient 5: Running in island, gen-sets synchronize/connect to microgrid to relieve discharged battery.

Unit	P set-point	V set-	Comments
Grid	-	-	Not connected
NaS	-2MW	0.995	
Fuel Cell	1MW	1.01	Uses Q vs. V droop
PV	0.6MW	-	
Gensets	1.08MW/unit	1.01	2.16MW total, identical sources
Capacitor	-	-	Connected

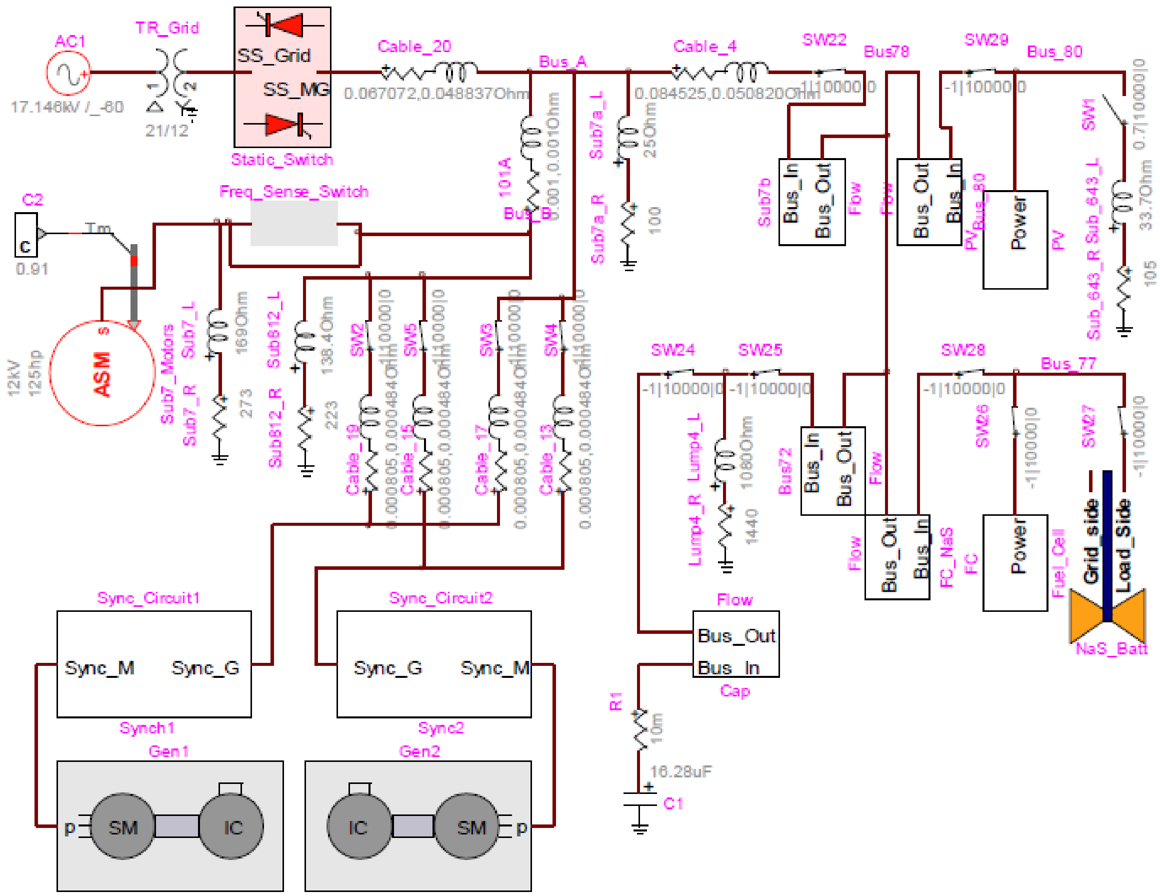


Figure 25 – Santa Rita Microgrid model utilized for back-up gen-set connection

The modeled gensets are 1.2MW units with 10% over-power capabilities. Once islanded, the gen-sets are connected to relieve the battery from the sole duty of tracking the load. Each gen-set was modeled identically and therefore the traces overlay entirely, so only one of the traces was included.

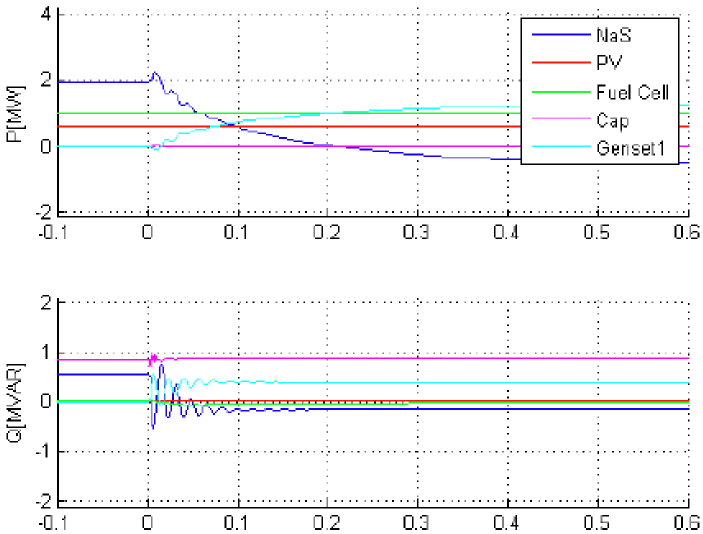


Figure 26 – Power and reactive power during gen-set synchronization/connection

Once connected, the power-transition between the NaS battery and the generators occurs over approximately 1/3 of a second. The power oscillations seen here are as a result of a non-zero load-angle during synchronization. The inertia of the gen-sets results in power fluctuations as the power accelerates and decelerates as a function of the position, resulting in a classical second-order response.

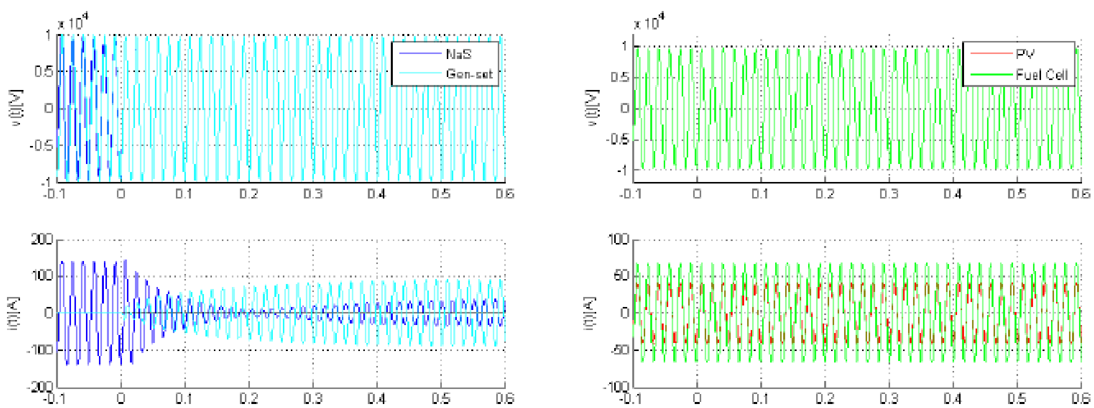


Figure 27 – Voltage and current after gen-set synchronization/connection

The synchronization process is evident from the relative blurring of the voltage waveform prior to t=0 and subsequent alignment of the voltage waveforms after synchronization. The power increase from the gensets and the subsequent reversal of power flow from the NaS battery is also evident in these figures.

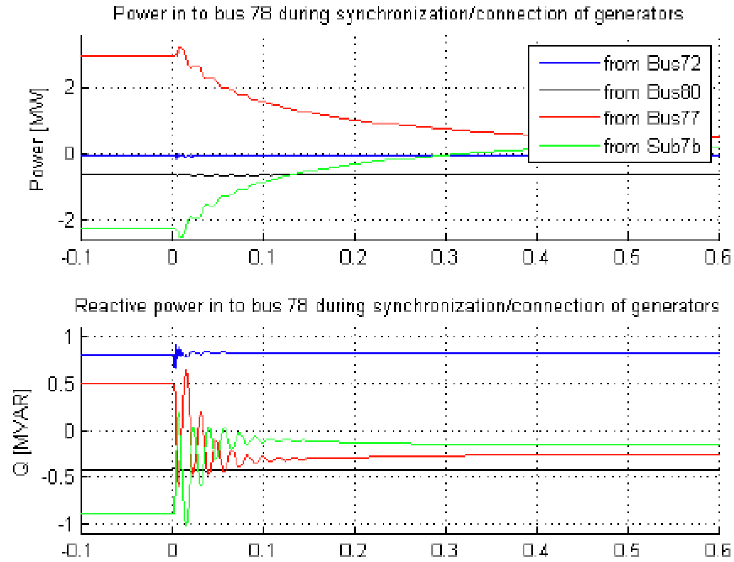


Figure 28 – Power flows in to bus 78 during synchronization/connection of gen-sets

The same power-flow redistribution seen in figure 26 can be seen here in figure 28.

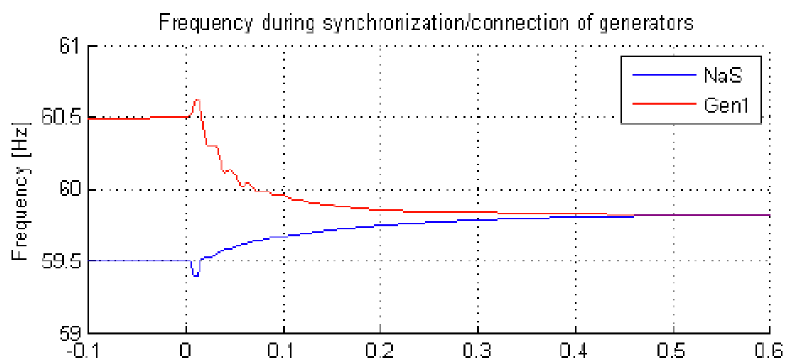


Figure 29 - Energy storage inverter frequency following island event

The frequency increases slightly once the back-up generators have connected and alleviated some of the loading on the battery inverter by loading the generators. The generators were modeled as identical units so the frequency of the second generator is the same as the first.

5 Microgrid Gen-set Grid Synchronization Transient Response

Paralleling Transients:

The issue of synchronous generators droop level within a microgrid system needs attention. This work focuses on reconnection to the grid through a static switch, which closes when the voltage phase angle across the switch is zero.

Grid synchronization of a synchronous-generator-based gen-set has been shown to exhibit frequency and power oscillations under certain circumstances. The following work investigates the conditions under which a 1.2MW generator set will oscillate dramatically and which conditions aid in a damped response.

Assuming a gen-set inertia of 0.75, which is between the upper and lower estimates for a MW scale machine, inertial effects dominate when the frequency is originally off by 3%. For a lower droop, this condition decreases drastically. Also, the no-load condition to which it is trying to settle causes the governor to rail against zero-output then oscillates away from it, creating a lightly damped state. Loading the machine gives more control to the governor as the torque to the machine is primarily within the operating constraints of a unidirectional power flow available from a diesel generator. This utilization of the operational range assists in damping. Overall, there is good correlation of the base case to data provided by Eaton. An alternative case results show that a smaller value of droop mitigates oscillatory response characteristics significantly.

5.1 Base case 1.

1.2MW generator

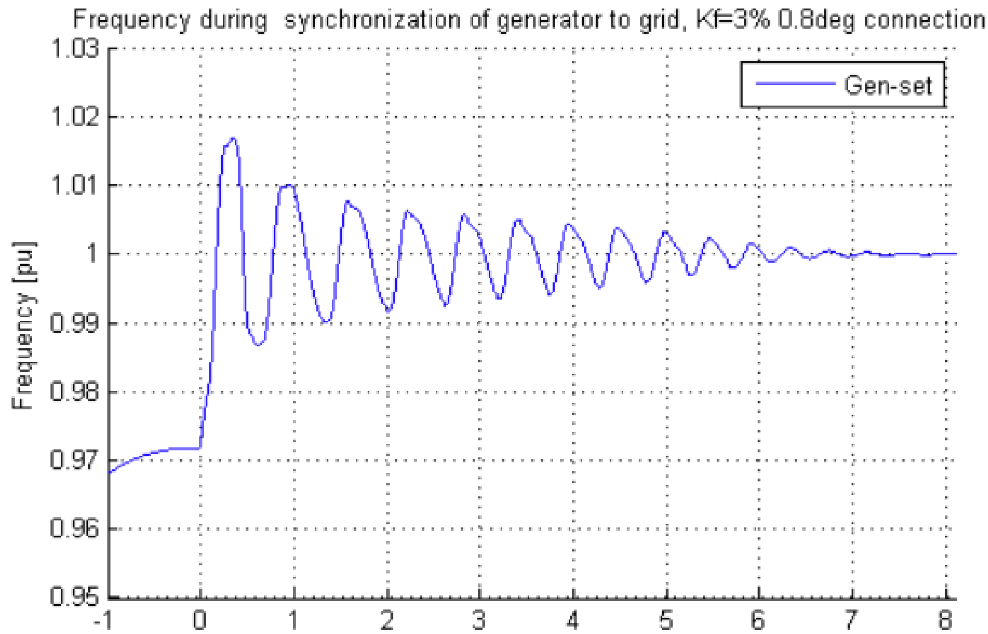
Droop 3% (1.8Hz)

$P_{set} = 0$

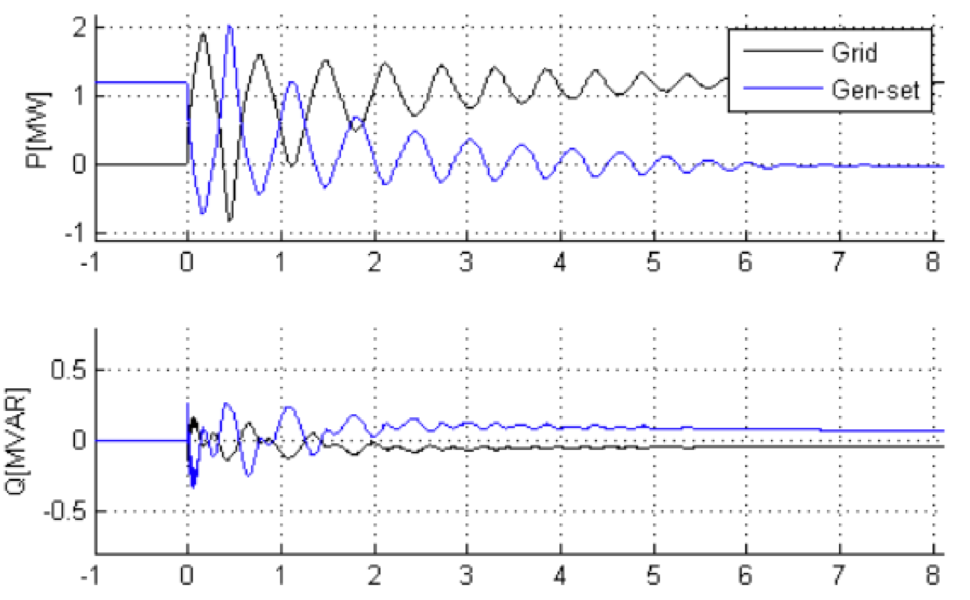
Load 1.2 MW

Island frequency ~ 58.2 Hz

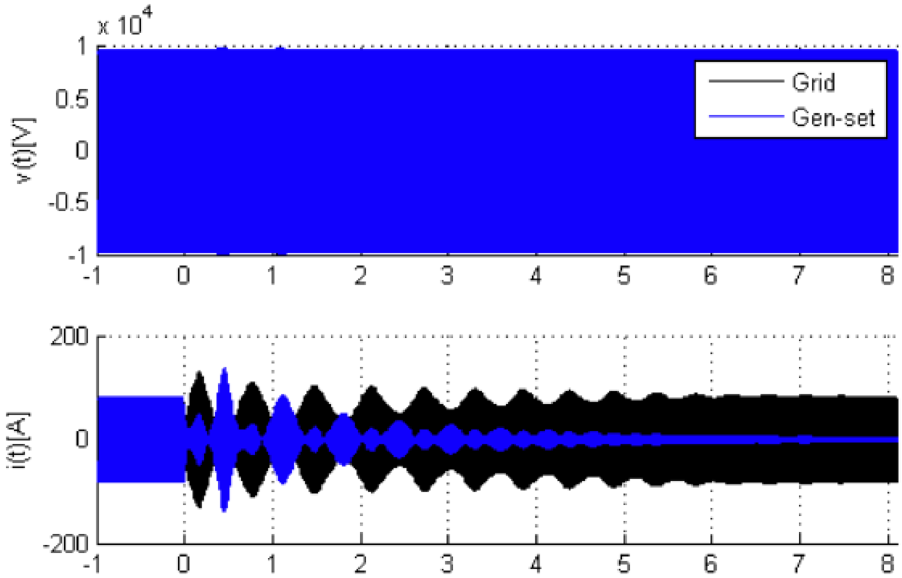
The generator has a power set point of zero, Pset=0 which is then fully loaded in island operation. This results in the machine operating at 58.2 Hz. The following transients are from closing the static switch at time = zero. This transient results in the power for the load being transferred from the generator to the grid.



In this base case, the frequency oscillations can be seen as having a damping ratio of approximately 0.15, where 4 oscillations reduce the magnitude of oscillation to half the original magnitude. The spring-like behavior comes from the impedance of the grid feeder, the input transformer, and the leakage reactance of the synchronous machine. The inertia comes from the synchronous machine and generator set.



The real power sum from the grid and gen-set equal the total load of 1200kW (1pu). The reactive power oscillates but is largely inconsequential.



The obvious current direction reversal is apparent from the current trace above. It illustrates the dramatic response characteristic of the connection transient under the base case conditions.

5.2 Alternate case 1,

1.2MW generator

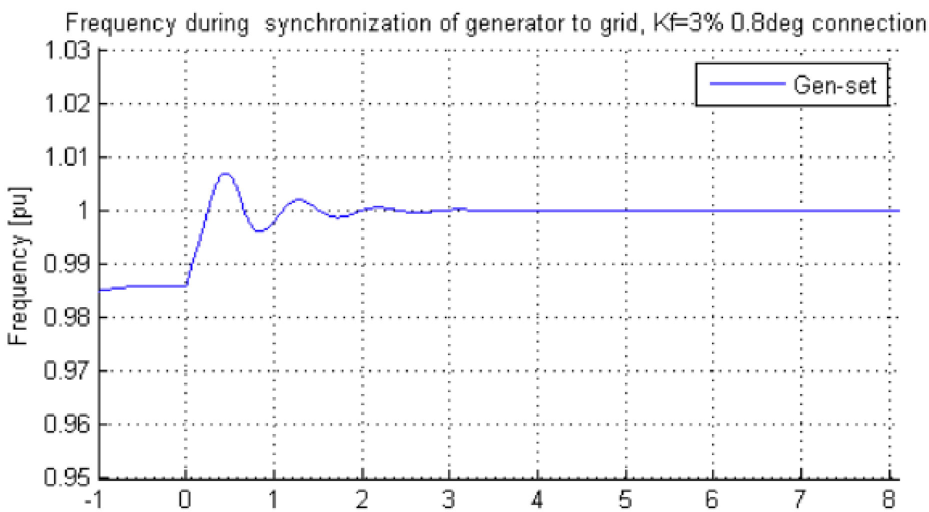
Droop 3% (1.8Hz)

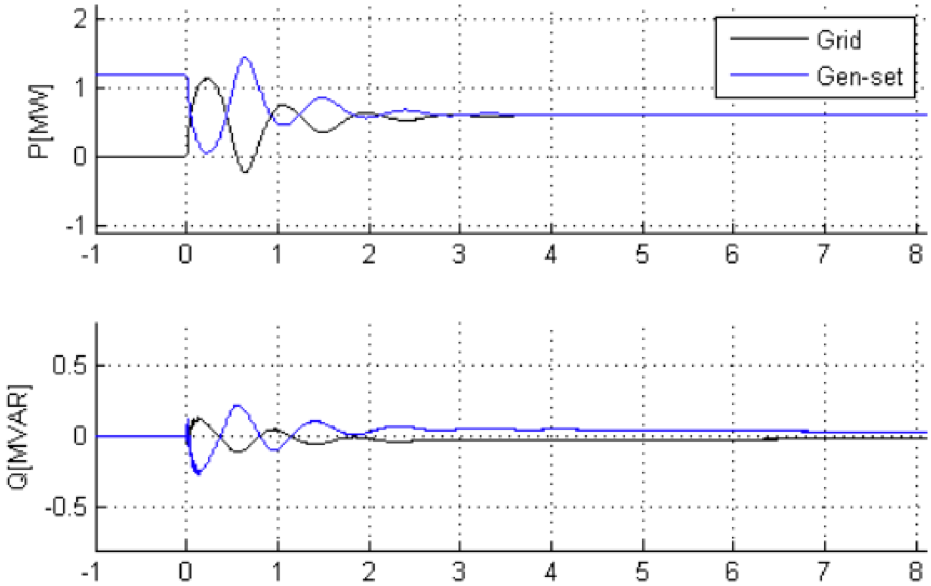
P_{set} = 0.6 MW

Load 1.2 MW

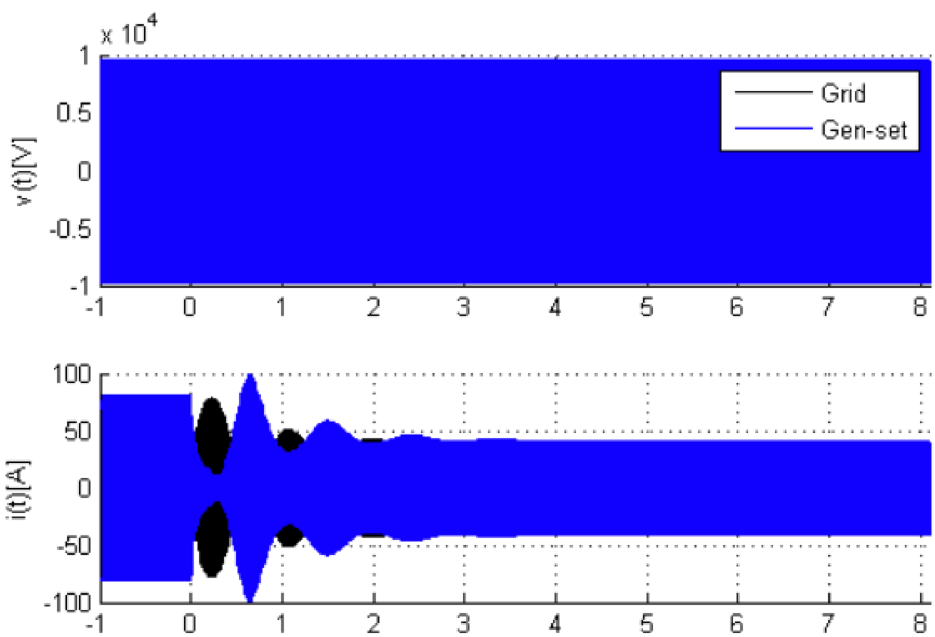
Island frequency ~ 59.1 Hz

As noted in the base case, the two primary components responsible for the response characteristics are the kinetic energy shift due to inertia, and the inability to command negative input torque from the prime mover. Here a power set-point of 0.5pu is used, which mitigates both effects and shows the benefits of simply lessening the difference frequency and allowing control of frequency via the prime mover input to be primarily within the input range.





It can be seen from the power that there still exists overshoot even past the previous maximum output. However, the oscillations damp in approximately 40% of the time as previously.



5.3 Alternate case 2.

1.2MW generator

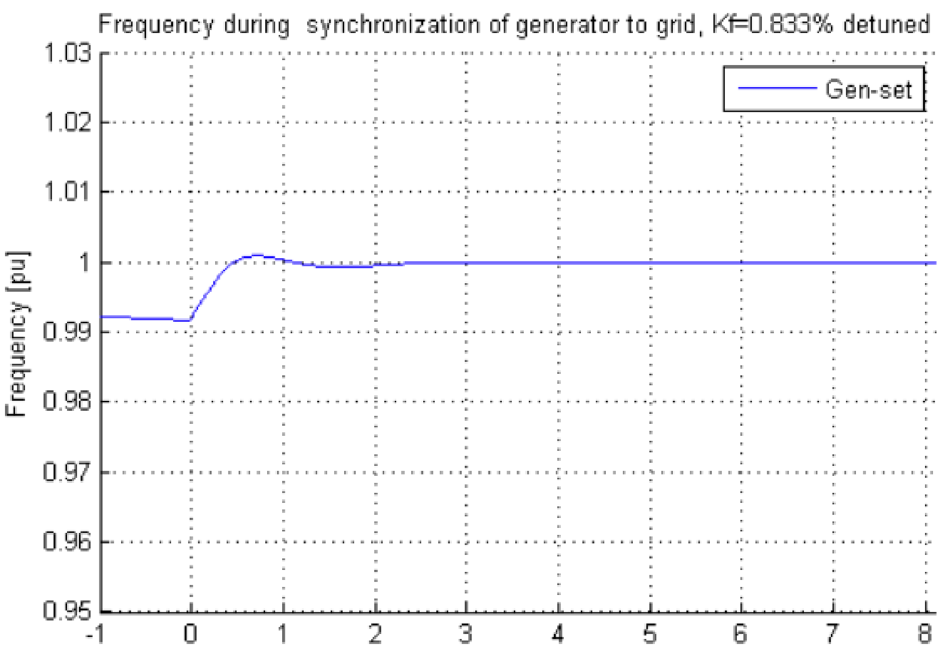
Droop 0.883% (0.5Hz)

$P_{set} = 0$

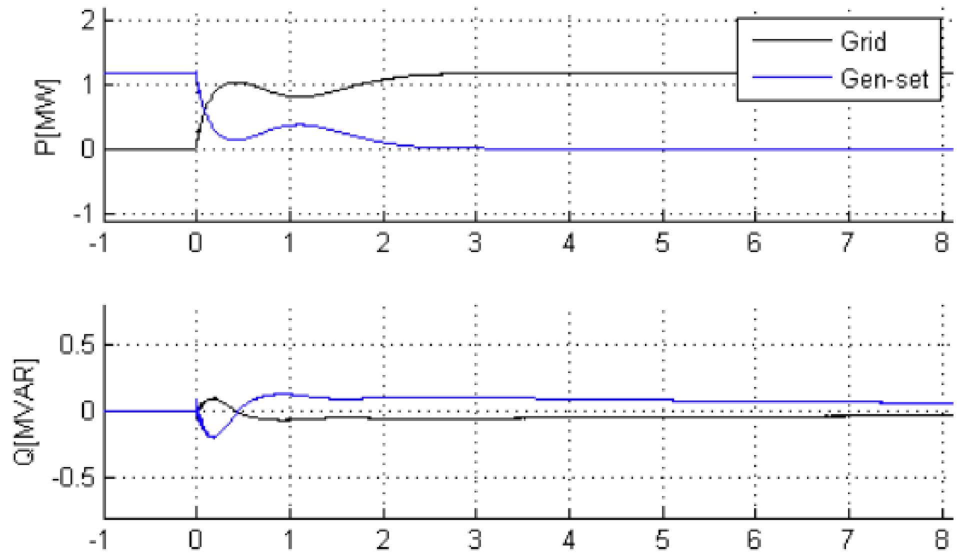
Load 1.2 MW

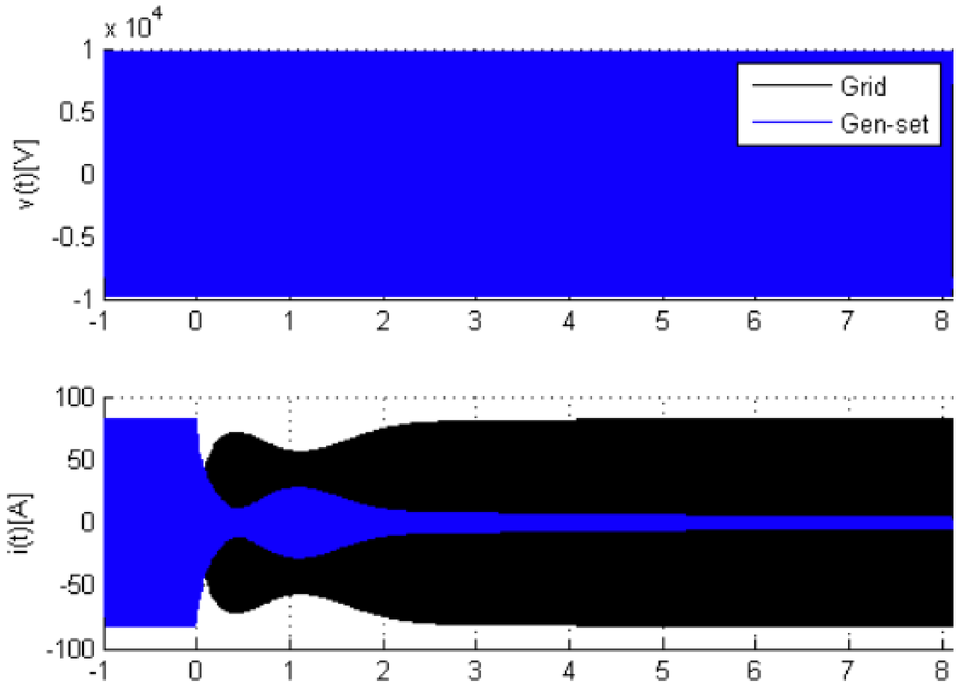
Island frequency ~ 59.5 Hz (worst case for CERTS droop)

This case utilizes the 0.5Hz droop utilized with the CERTS algorithms at UW-Madison and AEP Microgrids. Keep in mind that this connection transient represents the worst-case frequency difference that this network will experience and the response characteristic is dramatically improved over the previous two cases, exhibiting marginal overshoot and 20% of the settling time versus the base case.



The decreased droop gain allows for a more damped controller response as the frequency command is changed less as power deviations are measured. Also, the amount of kinetic energy dissipated in the damper windings of the synchronous machine is reduced by a factor nearly proportional to the change in droop gains (0.5/1.8). Overall this leads to less energy that needs to be dissipated in the generator and a more desirable response from a controller with identical gains to the base case.





Summary

This work indicates the importance of frequency droop. The last example utilizes the 0.5Hz CERTS droop used at UW-Madison and AEP Microgrids. It shows that for the worst-case frequency difference the system will experience minimal transients during paralleling to the grid. It is suggested that the generators droop be regulated to less than 1%.

6 Investigations of Gen-set Stall-Prevention within a Microgrid

ABSTRACT: *V/Hz control is a technique utilized by some generator-set manufacturers to prevent stalls in the event of large step load changes. It reduces the output voltage command with respect to reduced frequencies so that linear loads will draw less power and enable a recovery of the operating frequency back to a nominal level once the fuel governor has had time to compensate for the additional load. The work presented here investigates the usefulness of V/Hz in a microgrid by pairing it with an inverter-based microsource that is of equal size. The transient investigations illustrate two main points. First, by not reducing the gen-set voltage command with frequency, significant source-to-source reactive power flows during transient events are avoided. Second, the frequency excursion of the system in response to transients is significantly reduced when the added load is within the power margin of the inverter-based microsource. The fast load tracking abilities of inverters does seem to be a natural pairing for a genset to improve power quality.*

INTRODUCTION: Stall prevention is a serious issue in small/distributed generator sets as large changes in loading may cause the stall of a generator. These transients may also cause significant frequency excursions that are unacceptable for high power quality. Secondarily, the load supplying capability is dictated by the operational speed and below a minimum value (assumed 50 Hz, 0.833pu) the generator set is no longer capable of supplying rated output power and would result in a stall for rated loads. The set of simulations performed for this analysis provides some insight into whether the V/Hz control is necessary to prevent stalling of synchronous machine generator sets.

In the simulations here, the V/Hz rate for under-frequency conditions is 3pu voltage for 1pu speed. While this approach is sometimes useful at reducing output power in transient conditions when the speed dips due to large load transients, this method causes other issues when paired with other sources. Secondarily, the principle of V/Hz itself comes at the expense of high power quality where both voltage and frequency are deviant. More relevant to this analysis, however, is the issue of reactive power flow between sources when V/Hz is utilized in some but not all of the sources in the network.

This report is organized into two main sections, genset model validation that looks at a single genset and mixed system transient responses that includes a source pairing of a genset with an inverter microsource. The first section will demonstrate the agreement of the single-source generator set model with the actual test data to validate the genset model. The second section will illustrate the various response characteristics that a mixed system will have when an inverter microsource is added on the same islanded network as the genset. It will be demonstrated that the frequency excursion will be characterized by the proportion of load that is tracked by the genset. In the mixed system section the common transient loading condition will be the application of a 1pu load to an existing 1pu load, where the total rating of the mixed system is 2pu. By conservation of power, the amount of load that must be tracked by the genset is the remainder of load that is not able to be tracked by the inverter microsource due to power limit restrictions or power set-point considerations. This point will be discussed later.

6.1 Generator Set Model Validation

The generator set model used for this analysis follows a relatively simple continuous time model including prime mover governor, torque delay, machine inertia, flux-voltage synchronous machine model, voltage regulator, and V/Hz actions. The machine model is utilizing parameters extracted from nameplate data for the genset alternator whose values are included for reference in Table 1.

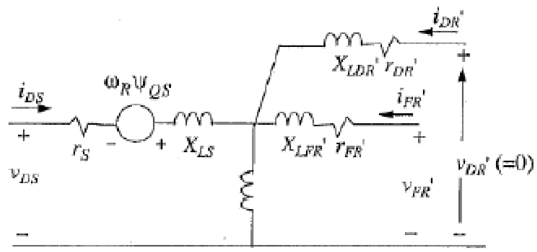


Figure 1 - Synchronous Machine equivalent circuit model including stator side leakage inductance (Xls), flux voltage ($\omega_R\Psi_{QS}$), damper windings (Xldr), field winding (Xlfr) and exciter voltage V_{FR} (Lipo, 2008). Model depicts D-axis circuit only with common magnetizing inductance Xmd (unlabeled). Q-axis lacks field circuit but retains damper structure.

Table 1 Generator Per-Unit values

Parameter	Value [pu]
Stator leakage:	0.024
Magnetizing, d-axis	2.764
Magnetizing, q-axis	1.347
Field leakage	0.163
Damper d-axis	1.24
Damper q-axis	1.24
Inertia	0.77

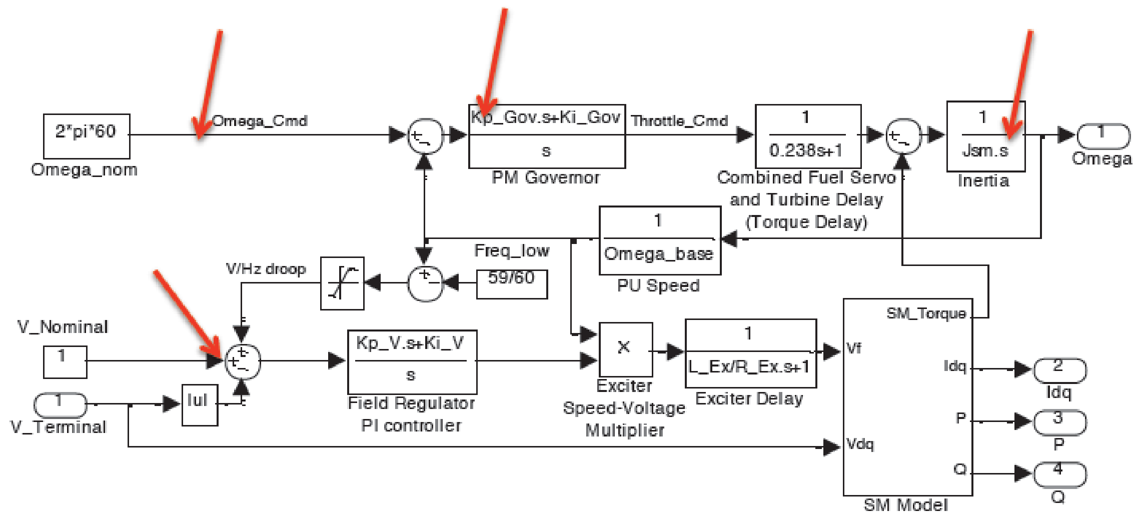


Figure 2 - Genset model including engine, governor, alternator and voltage regulator components modeled after (Krishnamurthy, 2008) and (Kariniotakis & Stavrakakis, 1995)

The relevant synchronous machine alternator equations are presented in equations 1-5 and the supporting equations to define the intermediate variables are presented in equations 6-11.

$$\frac{d}{dt}(\psi_{ds1}) = \left[\frac{r_s}{x_{ls}}(\psi_{md1} - \psi_{ds1}) + V_{ds1}\right]\omega_{base} + \omega\psi_{qs1} \tag{1}$$

$$\frac{d}{dt}(\psi_{qs1}) = \left[\frac{r_s}{x_{ls}}(\psi_{mq1} - \psi_{qs1}) + V_{qs1}\right]\omega_{base} - \omega\psi_{ds1} \tag{2}$$

$$\frac{d}{dt}(\psi_{dr1}) = \frac{r_{dr}}{x_{ldr}}(\psi_{md1} - \psi_{dr1})\omega_{base} \tag{3}$$

$$\frac{d}{dt}(\psi_{dq1}) = \frac{r_{qr}}{x_{lqr}}(\psi_{mq1} - \psi_{qr1})\omega_{base} \tag{4}$$

$$\frac{d}{dt}(\psi_{fr1}) = \left[\frac{r_{fr}}{x_{lfr}}(\psi_{md1} - \psi_{fr1}) + \frac{r_{fr}}{x_{md}}V_{fr1}\right]\omega_{base} \tag{5}$$

Equations 1-5 are based on a flux-voltage model of the synchronous machine which is more simple and accurate than a model using current as the state variables due to the need to calculate the derivative of the current in the latter case to determine flux voltages.

$$x_{md}^* = \frac{1}{\frac{1}{x_{ls}} + \frac{1}{x_{ldr}} + \frac{1}{x_{lfr}} + \frac{1}{x_{md}}} \tag{6}$$

$$x_{mq}^* = \frac{1}{\frac{1}{x_{ls}} + \frac{1}{x_{lqr}} + \frac{1}{x_{mq}}} \tag{7}$$

$$\psi_{md1} = \left(\frac{\psi_{fr1}}{x_{lfr}} + \frac{\psi_{dr1}}{x_{ldr}} + \frac{\psi_{ds1}}{x_{ls}}\right)x_{md}^* \tag{8}$$

$$\Psi_{mq1} = \left(\frac{\Psi_{qr1}}{x_{lqr}} + \frac{\Psi_{qs1}}{x_{ls}}\right) x_{mq}^{*} \tag{9}$$

$$I_{ds1} = \frac{\Psi_{ds1} - \Psi_{md1}}{x_{ls}} \tag{10}$$

$$I_{qs1} = \frac{\Psi_{qs1} - \Psi_{mq1}}{x_{ls}} \tag{11}$$

The supplementary equations 6-11 calculate the intermediate variables to simplify the preceding expressions. A block diagram would be cumbersome for the work here, but would be represented by the equations listed.

The relevant control parameters are included in Table 2.

Table 2 Genset model controller parameters

Genset Parameter	Value for Stock Genset	Typical Value
Governor proportional gain	Kp_Gov=6.7[pu-Fuel/pu-Speed]	0[pu-Fuel/pu-Speed]
Governor integrator gain	Ki_Gov=5.0[pu-Fuel/pu-Speed-sec]	3.33[pu-Fuel/pu-Speed-sec]
Torque production delay	Tau_filt=~0.238[sec]	0.2(NA)-0.5(w/Turbo)[sec]
Voltage regulator proportional gain	KpV=20 [pu-Volt/pu-Volt]	-
Voltage regulator integrator gain	KiV=90[pu-Volt/pu-Volt-sec]	-

The governor parameters in Table 2 correlate to Figure 2. These parameters were manually tuned in concert with the torque delay block to reasonable agreement with the transient response. The proportional gain and the inertia were tuned together to give the right frequency and magnitude of the primary oscillation resulting from the load transient. Increases in the proportional governor gain increases the frequency of the damped oscillatory response where the proportional gain can be viewed as spring stiffness in a mass-spring system. The inertia would then be the mass in the mass-spring system. The integrated governor term determines the ultimate rate at which the system achieves steady state after a transient, whereas the proportional governor gain primarily determines the maximum frequency excursion. The torque production delay generally decreases the stability of the system and was tuned by matching the damping of the test data. It represents the bulk delay between the fuel command and the torque production which incorporates the throttle/fuel-rail actuation by servo and a turbocharger turbine delay if so equipped. The turbocharger is typically the dominant delay characteristic so naturally aspirated systems will lack this delay and result in a generally lower overall delay. The voltage regulator block gains were tuned to match the nominal voltage response following transients. It is a generally fast and reasonably damped response, but the test data is largely non-linear which implies that the linear model is not very representative of the actual system, or that the data collection method may also be inconsistent. The V/Hz command interconnection is included to form the regulation and V/Hz effects.

Model vs. Test Data

A load application transient was performed to illustrate the agreement to the actual test data. Figure 3 shows a transient from 0% loading to 50% loading for a single islanded source. Figure 3 illustrates the general agreement between the simulation and experimental data. This is for isochronous operation shown in Figure 2 with V/Hz voltage regulator.

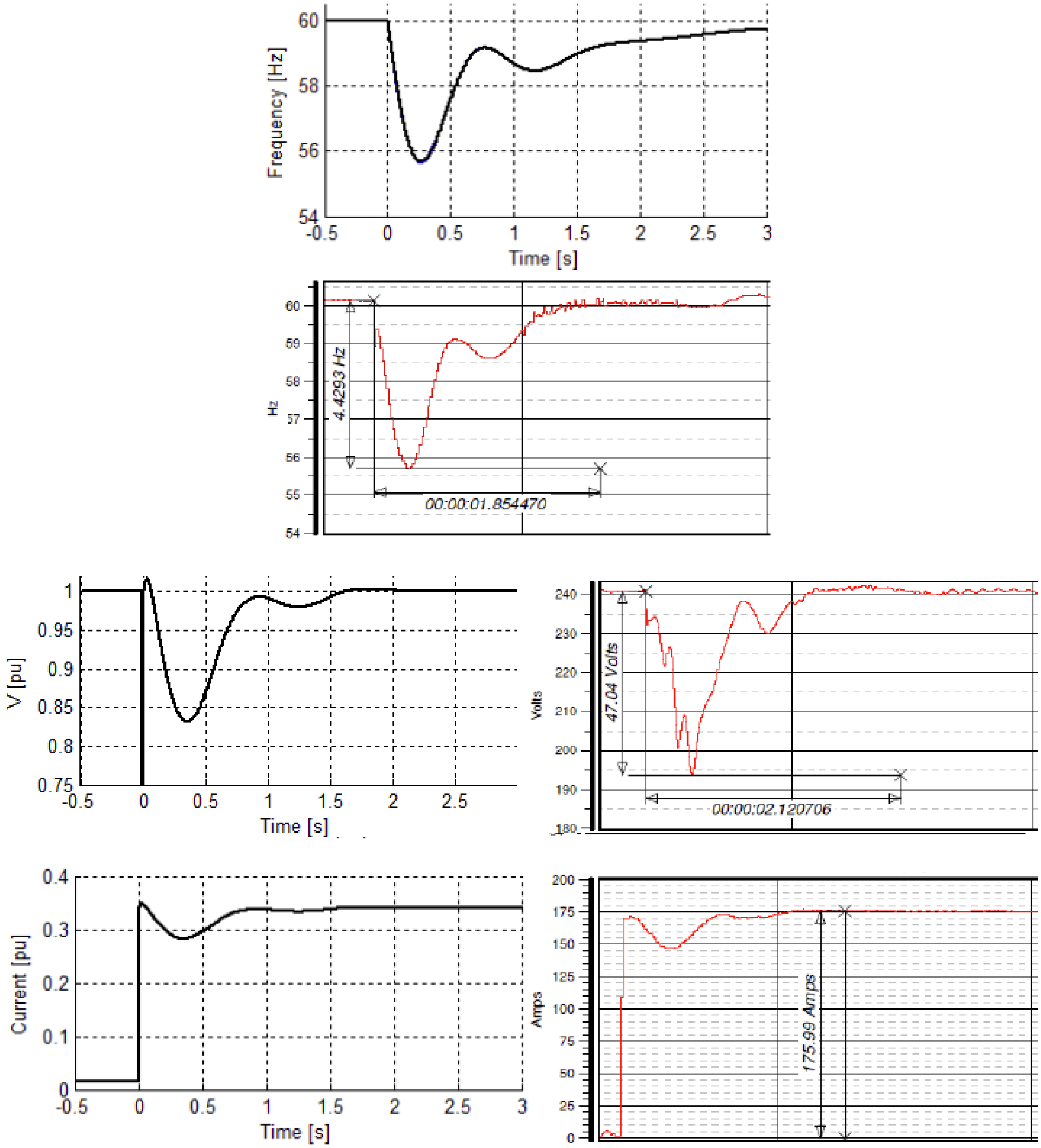


Figure 3 0-50% load application transient to a synchronous machines. Provided to show agreement with experimental transient data. Simulation is on left the actual test data on right.

A load removal transient simulation transient was also performed and the result is provided in Figure 4. It illustrates the surge in frequency as the governor reacts to the lower required output power. Again here, the agreement between the test data and the simulation is largely consistent. One important point to note is that rated current comes a 2/3pu in the model used here.

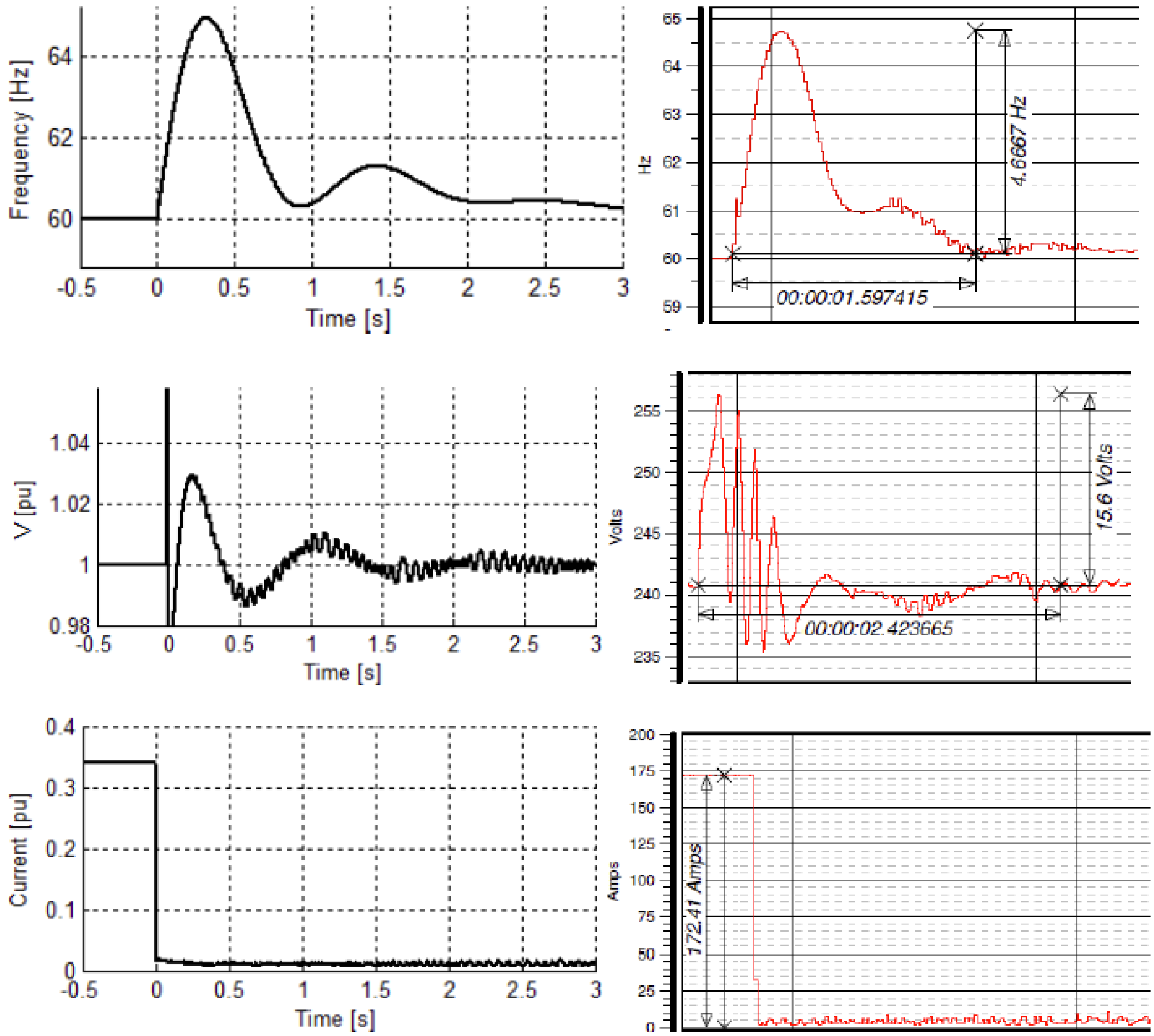


Figure 4 50-0% load removal transient for system with two identical synchronous machines. Provided to show agreement with experimental transient data.

Model effects of V/Hz Controller

To illustrate the effect of V/Hz control, two magnitudes of load transients were simulated with and without V/Hz control. Figure 5 demonstrates the resulting characteristic of a 75% load transient with and without V/Hz control. It can be seen that the power is reduced to less than half in the case with V/Hz control enabled. This reduces the frequency excursion from more than 8Hz to less than 6Hz which does not initially appear to be a significant result, especially when considering the voltage is reduced to 75% of the rated value to accomplish this. A 25% voltage magnitude deviation qualifies as a power quality event whereas the condition without the V/Hz control maintains a 5% voltage deviation, albeit with a larger frequency excursion.

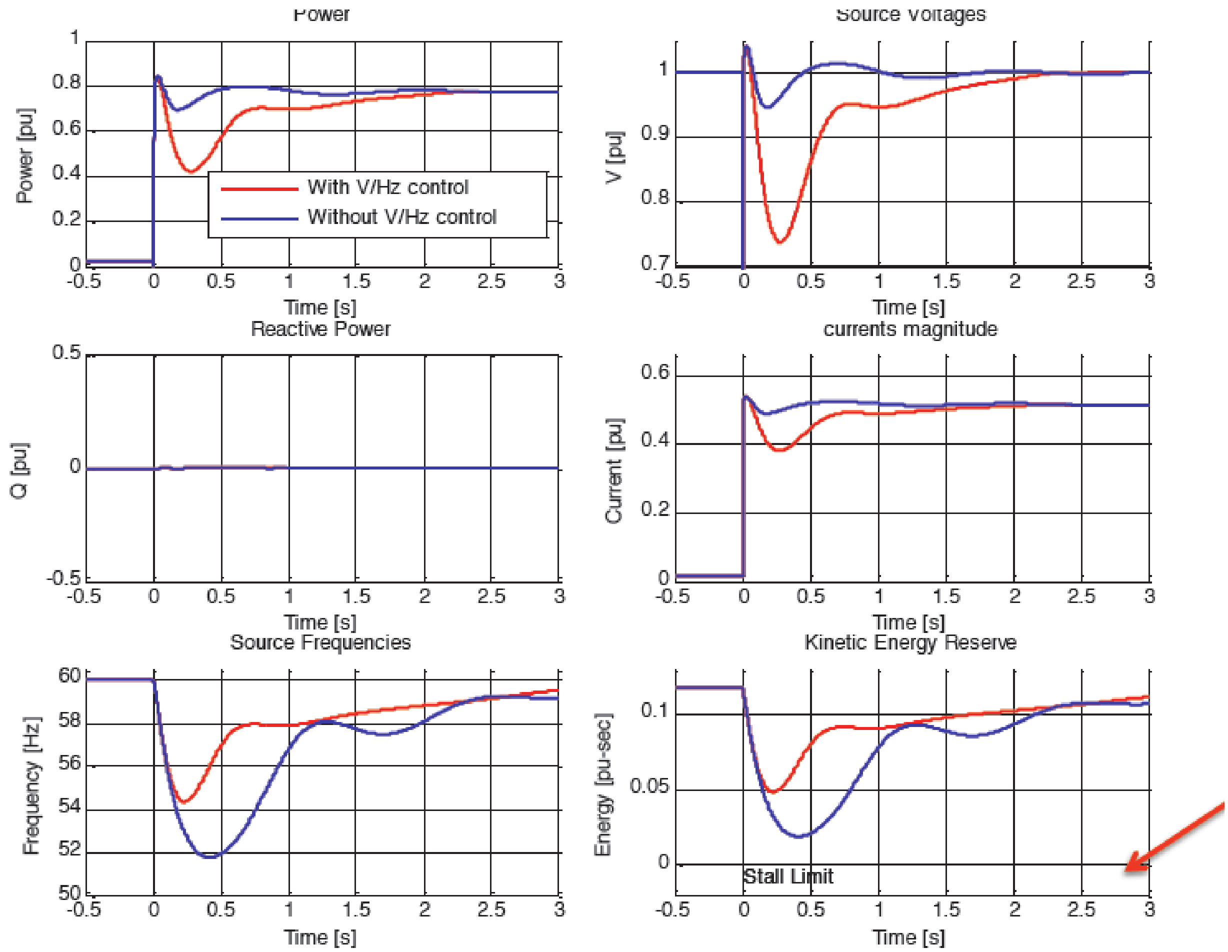


Figure 5 - Comparison of 75% genset load transient (2% to 77%) with and without V/Hz control

One important point to note from the transient in Figure 5 is the kinetic energy reserve of the two cases. The case without the V/Hz control comes much closer to the stall limit that the case with V/Hz control. This result indicates that without V/Hz control, the genset comes close to stalling for this load transient event. Note that this assumes when the machine operational speed is below a minimum value (assumed 50 Hz, 0.833pu) the generator set is no longer capable of supplying rated output power and would result in a stall for rated loads.

The next case in Figure 6 shows the effect of V/Hz control in the face of a 100% load transient where the absence of V/Hz control causes a stall. Therefore, this simulation indicates that this genset would not be capable of withstanding a 1pu load step without V/Hz control in a single-source island. This prompts the main question of how an inverter-based microsource will change the situation.

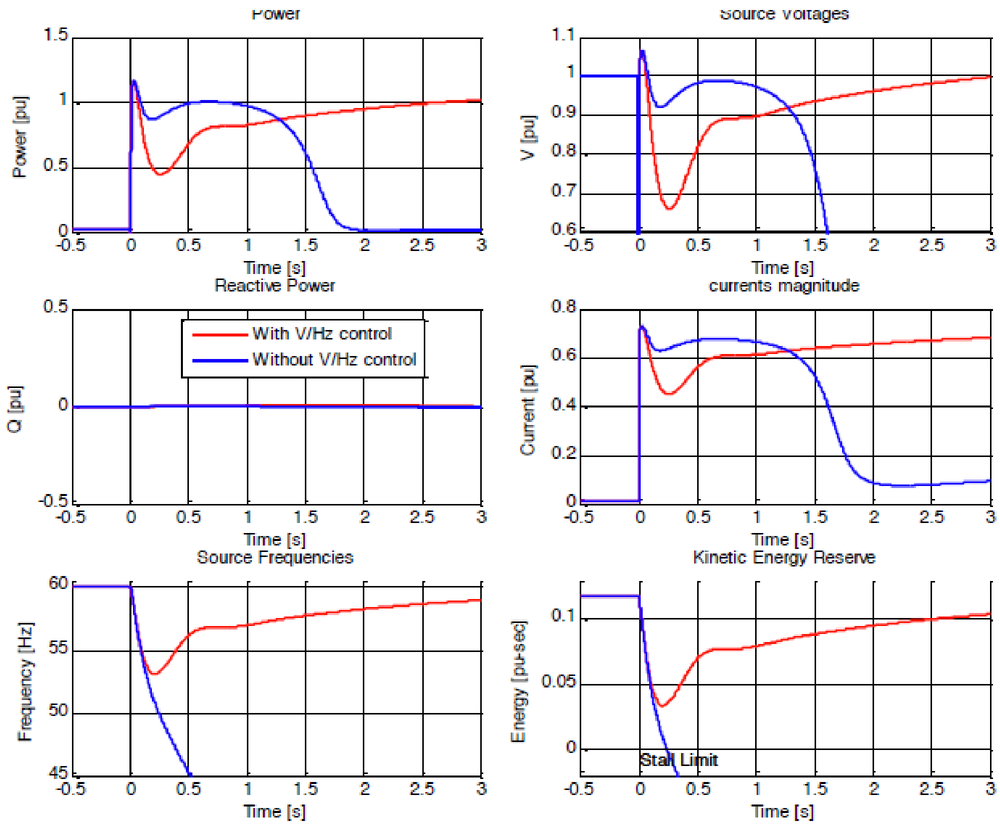


Figure 6 - Comparison of 100% genset load transient (2% to 102%) with and without V/Hz control

6.2 *Mixed System Transient Response*

In this section, transient responses will be investigated that represent the range of loaded conditions that a microgrid might encounter with a mixed system composed of inverter-based and rotating microsources. The genset model used here will be modified slightly to include the use of frequency droop and voltage droop algorithms to operate properly with other sources. Initially, however, the genset will be operated in stock fashion with isochronous frequency regulator, with the exception of the removal of the V/Hz control. The inverter microsource used in the mixed-system simulations is depicted in Figure 8 as a voltage source where the magnitude and frequency are near the rated values. This source uses voltage and frequency droop controls that help balance reactive and real power flows respectively. The Mq gain is used to reduce the output voltage magnitude when the source is supplying reactive power, akin to a fixed value of impedance (5% in this case). The Mp gain is set to 1% of the nominal frequency (Mp=3.77 [rad/s/pu-power]) to adjust the power output to the value of the power set-point when connected to a stiff 60Hz source. In addition to the frequency droop gain are power limiter gains that enable steady state operation to not exceed the power limits of the source. This controller engages only when power is measured beyond the maximum rated power and the time to return to the nominal limit is finite.

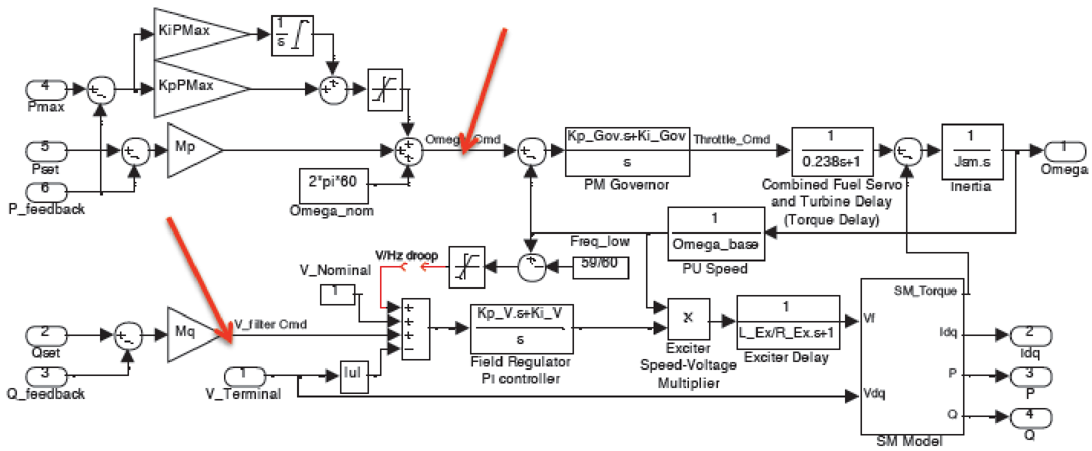


Figure 7 - Genset controller with added power and reactive power droop capabilities and selectable V/Hz control

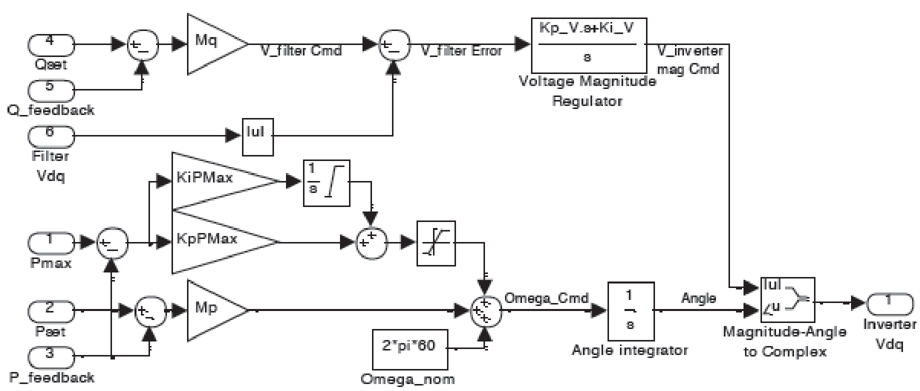


Figure 8 - Inverter Microsource model with frequency droop regulator, inverter filter voltage regulator and maximum power controller.

Table 3 - Microgrid source parameters relating to Figure 7 and Figure 8

Microgrid Source Parameters	Value for Genset	Value for Inverter	Units
Power vs. frequency droop gain	Mp=3.77	Mp=3.77	[rad/sec/pu-power]
Reactive power vs. voltage droop gain	Mq=0.05	Mq=0.05	[pu-Voltage/pu-Reactive power]
Power maximum P vs. f prop. droop gain	KpPMax=3	KpPMax=3	[rad/sec/pu-power]
Power maximum P vs. f int. droop	KiPMax=30	KiPMax=30	[rad/sec^2/pu-power]

gain			
Voltage regulator proportional gain	KpV=20	KpV=0	[pu-Volt/pu-Volt]
Voltage regulator integrator gain	KiV=90	KiV=46.88	[pu-Volt/pu-Volt-sec]
Power maximum (cont. rated power)	Pmax=1	Pmax=1	[pu-power]

Mixed System with Inverter in CERTS Droop and the Genset in Isochronous Mode.

As mentioned previously, the transient investigated here will bring the system from half its rated power to full rated power. The pre-transient load distribution between each source will be the primary variable here that dictates the system response. In each case the common resulting steady state will be for each source to be fully loaded. In the first transient, the inverter is fully loaded (1pu) prior to the transient and the genset is idling (0pu power). As the load is added, the genset is the only source with the additional operating margin and will fully track the additional load.

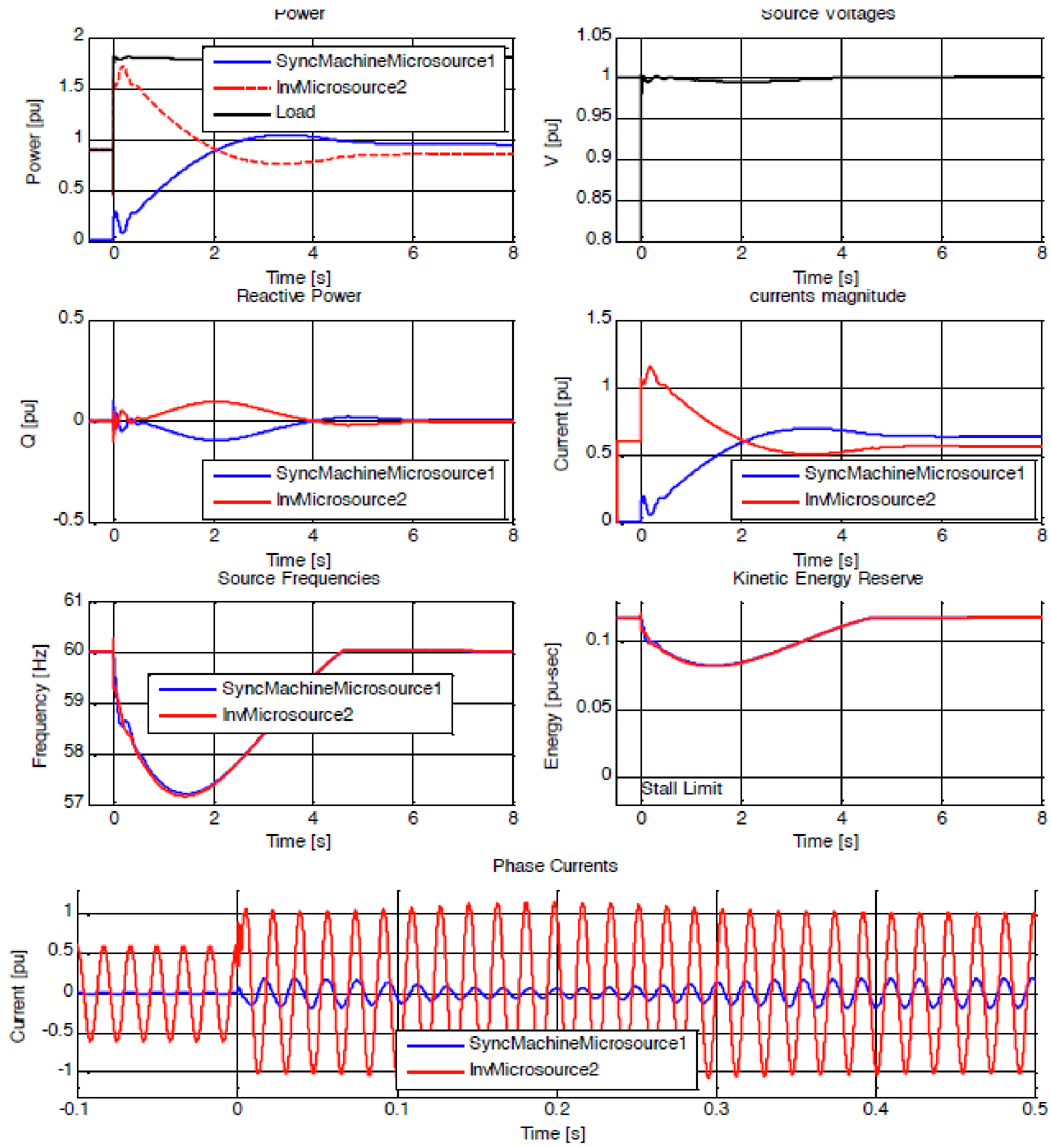


Figure 9 - Load application transient of 1pu in a mixed system. Genset is operated in isochronous mode with the V/Hz control disabled. Inverter power set-point is set to 1pu, which means that it is operating at its limit in steady state when the genset is in isochronous mode. This requires the synchronous machine to track the additional load.

The transient response in Figure 9 demonstrates the response in this case which is characterized by both the significant decrease in frequency as well as the initial overloading of the inverter source. As the added load is initially distributed based on the relative source impedances, it is not surprising that the inverter is sent into an overloaded condition. The reaction of the inverter microsource from its own maximum power controller is to reduce its frequency significantly. The synchronous machine follows in the decrease in frequency as the added load is still largely uncompensated from the governor action.

Another interesting point is that the genset is supplying the majority of the load (up to its 1.2pu physical limit) during the frequency recovery process. After the frequency had recovered, the power ultimately rebalances to 1pu each.

As a last note, the kinetic energy reserve is plotted to keep track of the remaining stored energy in the inertia of the genset. This value is calculated so that a 50Hz operation would be declared as zero remaining kinetic energy to remain consistent with the rated load capabilities of the genset. Assuming a constant torque generating capability of the prime move and the 120% typical peak overload rating, a 50Hz lower limit would be able to supply a maximum of 100% rated load without stalling.

The second case considers an equally loaded condition pre-transiently, where each source will be sharing the load tracking duties to supply the fully loaded system. This result is provided in Figure 10 and illustrates a very similar result as the first case with both frequency excursion and inverter overload. The main difference is the magnitude of each where the resulting characteristic is a combination of the load tracking characteristics of each source. However, due to the dominant characteristics of the genset response, the effects are primarily scaled by the amount of load that the genset must track.

Due to the power set-point of the inverter source being below 1pu, the steady-state resulting operating point would require the genset to produce 1.5pu output. However, the operational limit of the genset is around 1.2pu, which is limited by the prime mover and therefore results in a droop in frequency to 59.8Hz to draw the remainder from the inverter source. This condition is particularly bad for the genset as the generator is likely not rated for continuous output at this overloaded state and points to the fact that isochronous control should be avoided in paralleled operation with droop-controlled sources.

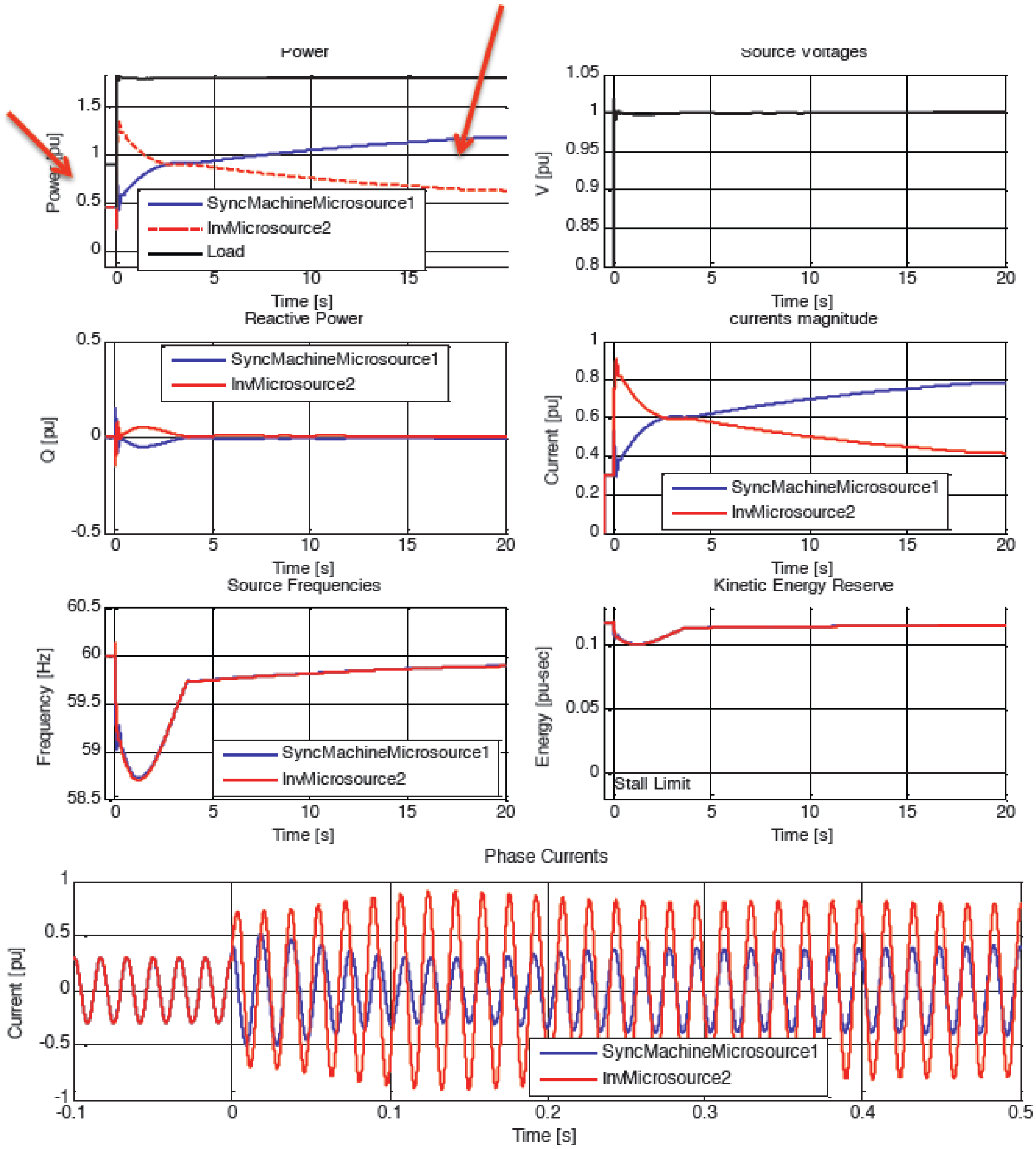


Figure 10 Load application transient of 1pu in a mixed system. Genset is operated in isochronous mode with the V/Hz control disabled. Inverter power set-point is set to 0.45pu, which means that both sources have operating margin and will share load tracking responsibilities.

The final case, Figure 11, places the genset at full load pre-transiently, leaving the inverter with enough operating margin to track the entirety of the added load. What can be seen is a relatively well behaved response with high power quality and significant amounts of damping. As might be expected from the previous case, the load is biased towards the genset due to isochronous control. However the mixed system takes slightly less time to achieve steady state (~2.5sec) as compared to the previous cases.

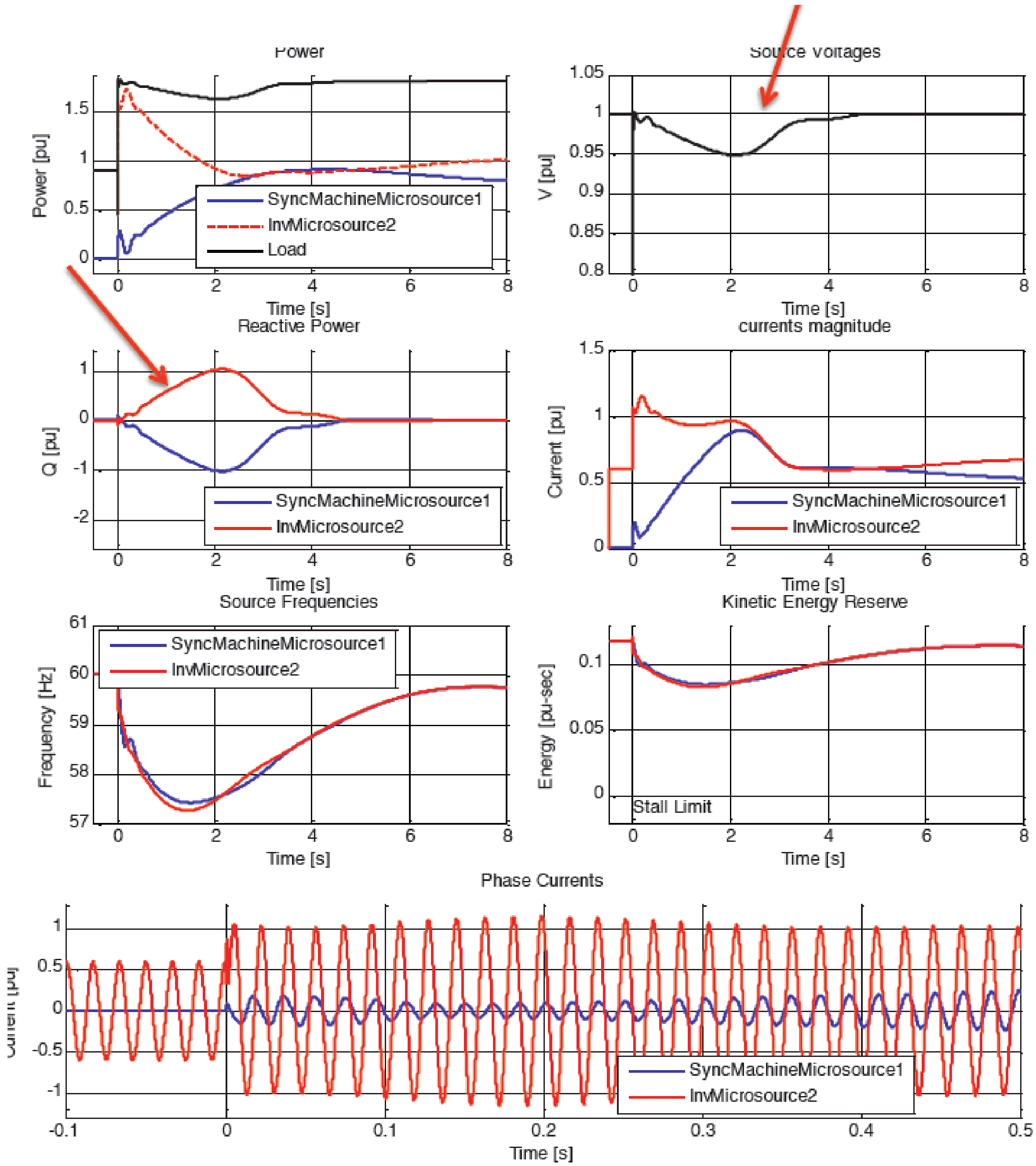


Figure 12 - Load transient with inverter and genset system. Power set point of inverter is 0.9pu, genset is set to 0pu (Pset1=0.9; Pset2=0). Both utilize frequency droop, V/Hz control is enabled for the genset only.

The inverter microsource has a voltage droop characteristic which limits but does not eliminate the reactive power as seen by the 1pu reactive power and the 1pu current magnitude that results between the sources. If it can be assumed that the inverter is capable of this operation, the transient is survivable, but with significant amounts of unnecessary reactive power flow between sources. This result points further to the inability of V/Hz control to be used in a microgrid without the same logic being implemented universally amongst all sources on the network.

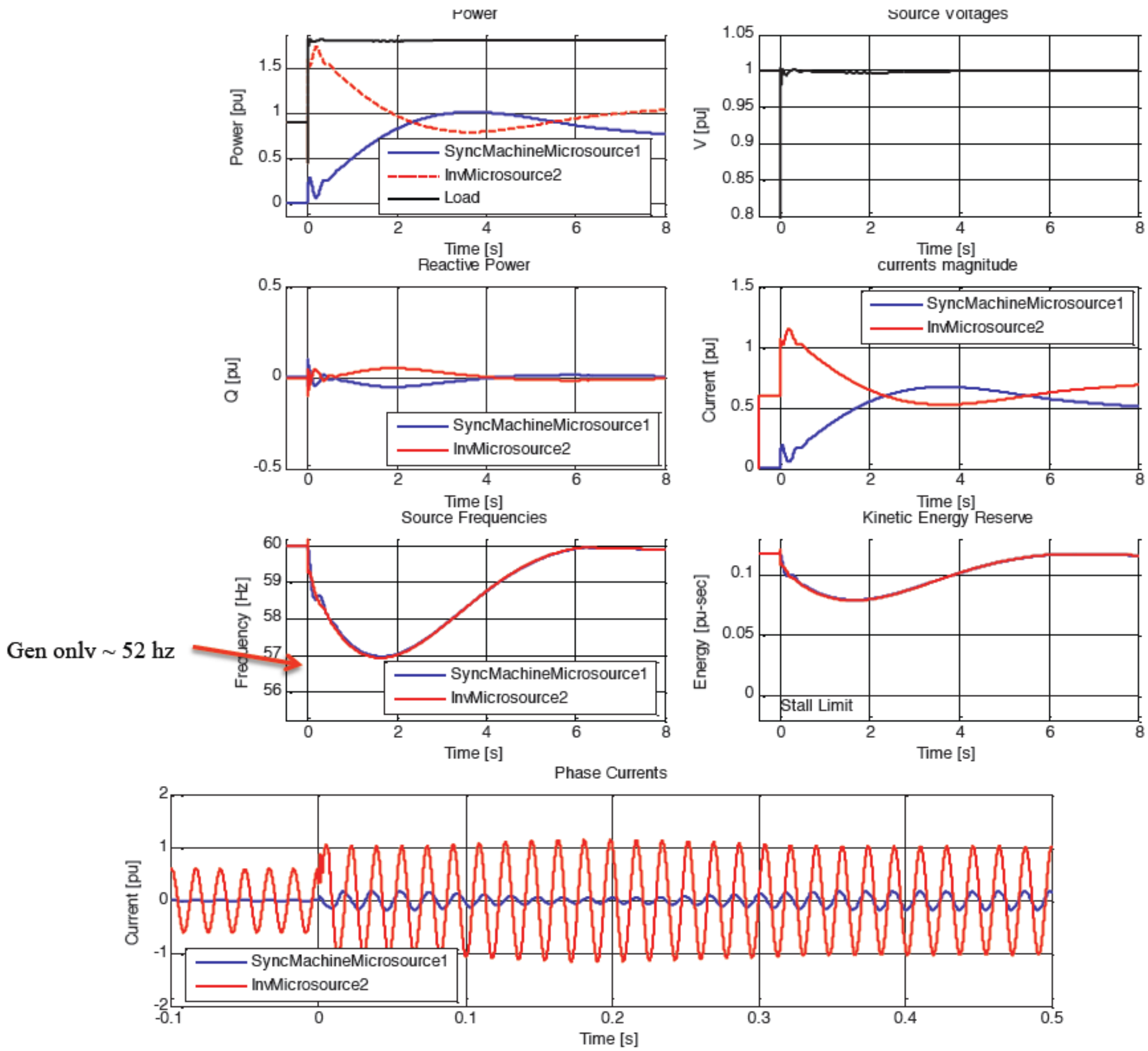


Figure 13 - Load transient with inverter and genset system. Power set point of inverter is 1pu, genset is set to 0pu (Pset1=0.9; Pset2=0). Both utilize frequency droop, V/Hz control is not utilized.

To examine a more appropriate configuration for a genset in a mixed-system microgrid, the voltage and frequency droop controllers were added to the genset as depicted in Figure 7. In the case of Figure 13, the inverter is initially loaded to a maximum point before the load transient, requiring the genset to track the additional load. This resulted in a slightly less of a frequency excursion as compared to the genset-only case due mostly to the overload energy drawn from the inverter. This change would be scaled in other pairings by the amount of overload energy allowed by the inverter power maximum controller. Higher gains would reduce the overload energy supplied and provide less transient support.

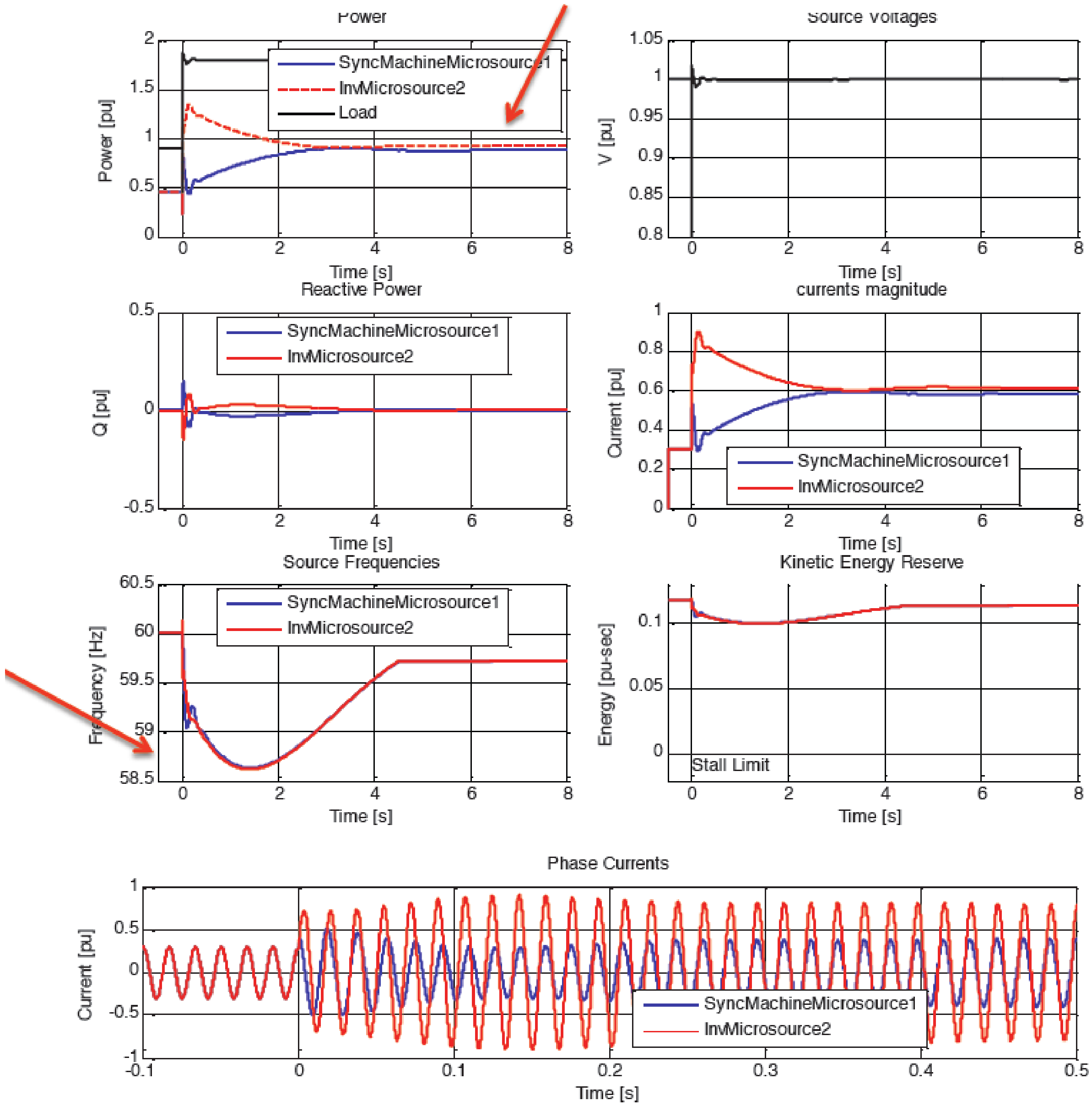


Figure 14 - Load transient with inverter and genset system. Power set points are equal (Pset1=0.45; Pset2=0.45). Both utilize frequency droop, V/Hz control is not utilized.

The equally loaded microgrid case is presented in Figure 14 and demonstrates approximately half the frequency excursion as the previous case which indicates that the amount of load tracked by the genset is proportional to the frequency excursion. At t~4.5sec, the system frequency reaches a point where the inverter exits the power-limited mode and the power limit controller disengages. While the inverter can be seen to operate within the rated power for approximately three seconds at that time, the energy saved in those three seconds is nearly equal to the over-energy provided in the first two seconds following the transient. This energy balance property is inherently embedded in the power limit controller as a linear controller.

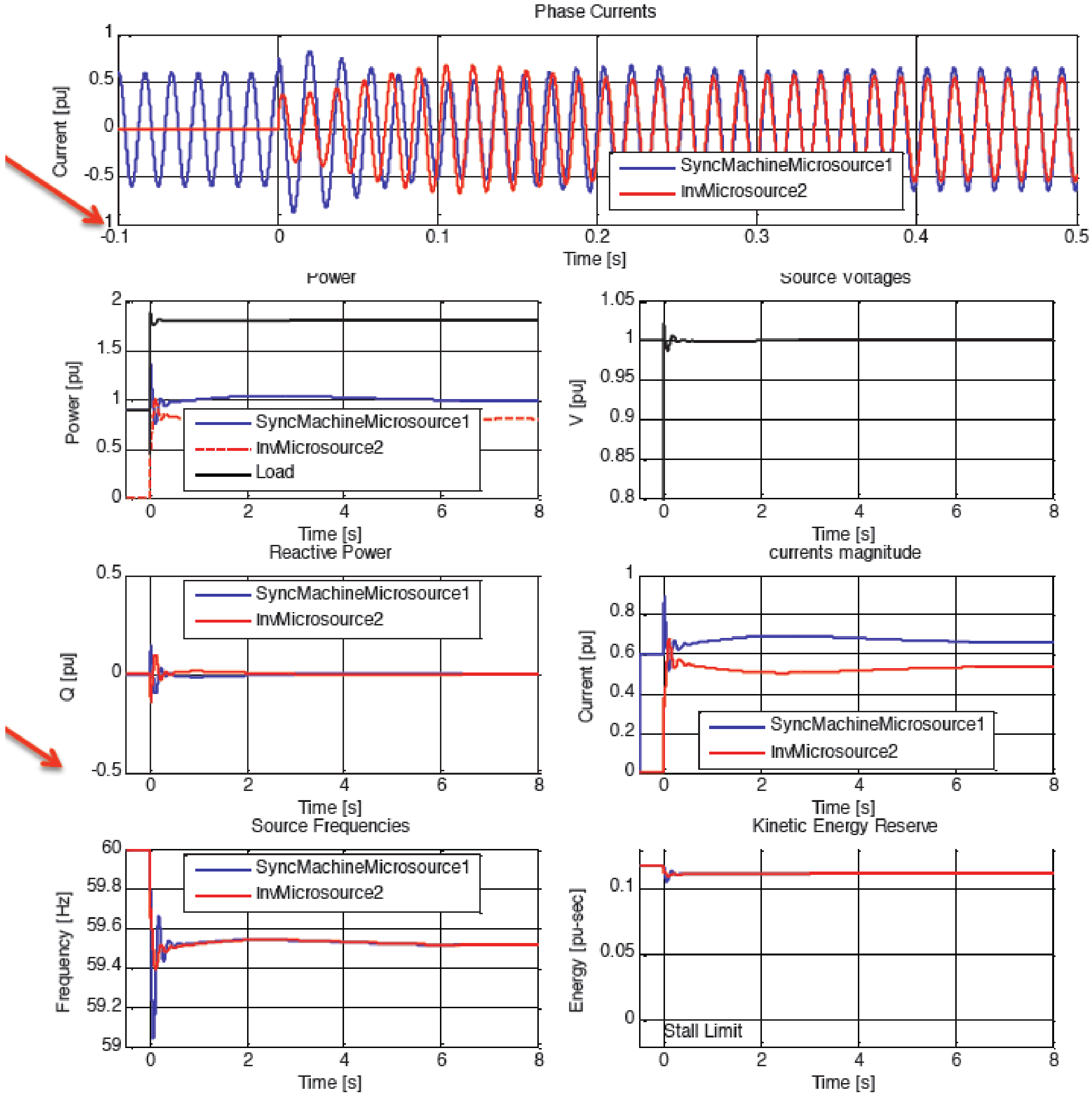


Figure 15 - Load transient with inverter and genset system. Power set point of the genset is 0.9pu and the inverter is 0pu (Pset1=0.9; Pset2=0). Both utilize frequency droop, V/Hz control is not utilized.

Pg~ 0 df~ 57

Pg~ 0.5 df~ 58.5

Pg~ 1 df~ 59 time much smaller

Another point to note is that the power maximum controller allows the genset to avoid operation against its prime mover limit of 1.2pu, Figure 10, and therefore avoids issues with continued use beyond the continuous rated power.

The last case presented here in Figure 15 illustrates the ideal condition where the additional load is entirely tracked by the inverter. The well-damped fast response is demonstrated, also resulting in a minor frequency excursion for the system, providing the highest power quality. This result requires that operating margin exists in an inverter-based source, but suggests that microgrid solutions that utilize inverter based sources perform better in the cases presented than gensets alone with respect to power quality.

6.4 Conclusion

The transient conditions included here provide evidence to four facts regarding stall prevention. First, the V/Hz concept was not demonstrated to be necessary in a mixed system to maintain system stability. Secondly, it was demonstrated that V/Hz control does not work well with other sources that do not include the V/Hz characteristic, reducing power quality and increasing unnecessary reactive power flows. Thirdly, stall prevention is an issue that should be considered in the context of the amount of load that the synchronous machine generator must track, which varies with the relative system loading. Lastly, isochronous control is not compatible with microgrid applications and may cause extended operation at the maximum output.

Every system has a maximum transient load limit and large loads can be supplied briefly from the inertia of a rotating generator. Depending on the overload energy capabilities of inverter microsources and their associated power control gains, inverters may or may not be able to aid in the support of excessive loads. The higher the integrator power limit gain, the less effective inverter inertia is demonstrated and the less the inverter will sustain acceptable frequencies in response to temporary transient loads.

Works Cited

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Krishnamurthy, S. (2008). *On the modeling and control of wound field synchronous machine based gensets for operation in a microgrid environment.* Madison: University of Wisconsin - Madison.

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APPENDIX E: Testing and Commissioning

Full MicroGrid System Commissioning - 3/27/13 (Day 1)

DESCRIPTION:

Final commissioning of load shed system. Testing grid-connected, island, emergency and outage modes.

Yellow highlights indicate where a load shed or outage **may** occur. Red text indicates where a load shed or outage **will** occur.

RESPONSIBLE PARTIES (RP):

Chevron Energy Solutions (CES) – Jay McCaa, Eduardo Alegria

Santa Rita Jail (SRJ) – Dan Lichtenberger

Encorp – Don Clover

OUTAGE RESTORATION PLAN

1. On standby in front of generator with flashlight; Reset relay; Reset HMI alarm
2. At PCC, open M1, close bypass switch, close test switches to relay, close M1
3. BEI on standby to manually close M2

PROCEDURE	Target Start Time	Actual Start Time	RP Verification	Comments/Additional Actions Performed
1) Verify following pre-testing system conditions: ☐ Battery system is online and operating in DERMS mode. ☐ PCS is operating in voltage source mode and remote	**7:30 A.M.**	8:20		DERMS operating in manual mode

☐ Fuel cell is online ☐ All test switches closed at IEM panel ☐ Motor pack is connected to bypass switch ☐ SLC Master Enable/Disable is ENABLED ☐ Battery SOC between 50 – 85%				Battery SOC = 86%
ISLAND MODE TESTING (Duration ~30 Minutes) 2) Verify bypass switch is closed and isolation switch is open.	**8:30 A.M.**	8:24		
3) Place bypass and isolation switch in remote control.		8:24		
4) Start Static Disconnect Switch (SDS) from HMI.		8:24		
5) Verify isolation switch closes and bypass switch opens.		8:24		
6) Place SDS in remote control.		8:24		8:26 - Added step: Trip battery to ensure SDS will bypass itself; Battery connection restored and SDS started
7) Simulate grid outage by removing grid side voltage signal. (1→2)		8:40 9:00		SOC = 82% Retested at 9:00
8) Verify microgrid successfully islands.		8:40		8:40 - PV1 and PV2 shed, then PV2 added backed but not PV1

		9:00		9:00 – PV did not shed
9) Open voltage signal to SEL 351 and UPC (TSM1A – G, H, I; TSM1B – G, H, I; TSUPC G, H, I).		8:40 9:00		8:40 - Jump to Step 54C
10) Verify M1 stays closed.		8:40 9:00		
ISLAND MODE HIGH AND LOW STATE OF CHARGE (Duration ~120 Minutes) 11) Verify the following Island Mode settings at the SLC: ☐ SOC Delay timers (all 4) are 10 seconds ☐ Lo Battery SOC Level, Shed C Loads is 23% ☐ Lo Lo Battery SOC Level, Shed B Loads to 21% ☐ Hi Battery SOC Level, Add B Loads is 27% ☐ Hi Hi Battery SOC Level, Add C Loads is 29% ☐ Battery SOC Level, Shed PV to 88%, 90%, 92%, and 94% for the four inverters ☐ Battery SOC Level, Add PV to 80%, 82%, 84%, and 86% for the four inverters.	**9:00 A.M.**	9:05		
12) In ISaGRAF, Encorp to force the battery state of charge level to 91%. (2→2G)		9:05		
13) Verify PV1 and PV2 are shed.		9:05		On HMI display, PV output appears to ramp down instead of

				instanteous shed.
14) In ISaGRAF, Encorp to force the battery state of charge level to 70%. (2G→2)		9:06		
15) Verify PV are added.		9:06		PV output ramps up once enabled
16) Verify the Diesel starting setpoint is at a Battery State of Charge Level 25% and the turn off setpoint is at a Battery State of Charge Level of 60%.		9:14		
17) Read Battery SOC. If SOC is more than 60%, closely monitor actual SOC in steps 18 – 25.		9:35		SOC = 74%
18) In ISaGRAF, Encorp to force the battery state of charge level to 24% (2→2A) Manually ramp up diesel generator to Max Generator %.		9:36		Limited to 20% 9:41 – Ramped to 40% 9:42 – Ramped to 50%; chiller brought online to increase facility load 10:00 – Ramped to 70%
19) Verify the following: ☐ Diesel generators come online at the same time. ☐ Verify loads, PV and Fuel Cell are not shed. ☐ Verify 32 relay does not trip the diesel generator and both		9:36		

stay online when in island mode with the battery online. Read power flow values to confirm. ☐ Verify load sharing across diesel generators. ☐ Verify Generator 1 KW display on SLC HMI				
20) In ISaGRAF, Encorp to force PCS battery KW charge rate to be higher than the Max Battery Charge Rate setpoint.		9:50		When diesel gen output at 52%, battery reached max charge rate
21) Verify diesel geneators decrease output such that the PCS battery charge rate equals the Max Battery Charge Rate.		9:50		Diesel gen output oscillated b/w 47 – 52% to maintain charge rate
22) In ISaGRAF, Encorp to force the battery state of charge level to 65% (2A→2)		10:05		Actual SOC entered ~80%
23) Verify diesel generators shut down.		10:05		
23A) In ISaGRAF, Encorp to force the battery state of charge level to 24% (2→2A) Automatically ramp up diesel generator to Max Generator %.		10:16		Max generator output set to 70%
23B) Verify the following: ☐ Diesel generators come online at the same time. ☐ Verify loads, PV and Fuel Cell are not shed. ☐ Verify 32 relay does not trip the diesel generator and both stay online when in island mode with the battery online. Read power flow values to confirm.				Gen 1 came online slightly before Gen2 Ramped to 67% before controlling output of battery. Diesel gen output oscillated b/w 65 – 68% to

☐ Verify load sharing across diesel generators. ☐ Verify Generator 1 KW display on SLC HMI				maintain charge rate
23C) In ISaGRAF, Encorp to force the battery state of charge level to 65% (2A→2)		10:20		
23D) Verify diesel generators shut down.		10:20		
24) Put diesel generators in manual mode to avoid restarting during island mode testing.		10:26		
25) In ISaGRAF, Encorp to force the battery state of charge level to 22% (2→2A→2B)		10:34		
26) Verify ALL enabled C loads are block shed after 15 seconds and no B loads are shed.		10:34		
27) Verify alarm "Island Mode, Battery Capacity Lo, Shed C Load" is received.		10:34		
28) In ISaGRAF, Encorp to force the battery state of charge level to 20% (2B→2C)		10:38		
29) Verify ALL enabled B loads are block shed after 15 seconds		10:38		

30) Verify alarm "Island Mode, Battery Capacity Lo Lo, Shed B Load" is received.		10:38		
31) In ISaGRAF, Encorp to force the battery state of charge level to 28% (2C→2B)		10:39		
32) Verify alarm "Island Mode, Battery Capacity Lo Lo, Shed B Load" clears.		10:39		Alarm has to be cleared from HMI before loads add back
33) Verify B loads sequentially added in 10 second steps.		10:40		
34) In ISaGRAF, Encorp to force the battery state of charge level to 30% (2B→2A→2)		10:40		
35) Verify alarm "Island Mode, Battery Capacity Lo, Shed C Load" clears.		10:40		
36) Verify C loads sequentially added in 10 second steps.		10:40		
ISLAND MODE – LOSS OF COMMUNICATION TESTING (Duration ~30 Minutes) 37) Put diesel generators back in automatic mode.	**11:00 A.M.**	10:45		
38) In ISaGRAF, Encorp to force the battery state of charge level to		10:45		

24%.				
39) Verify both diesel generators come online.		10:45		
40) Simulate loss of communication with the battery and SLC.		Day 2		
41) Verify the system goes into local control and loads and Fuel Cell do not shed. Verify PV sheds.		Day 2		
42) Restore communication with battery and verfiy the system operating mode returns to "island Mode" and PV is added.		Day 2		
43) Charge battery to 75% SOC.		Day 2		
ISLAND MODE TO EMERGENCY MODE TRANSITION TESTING (Duration ~30 Minutes) **44) Simulate battery outage by turning off battery at battery HMI. (2A→3)** Contact FCE Global Technical Assistance Center (GTAC 1-800-326-3052) to notify initiation of HSBY.	**11:30 A.M.**	11:10		
45) Verify the following: ☐ Fuel Cell, PV and C loads shed ☐ A and B loads do not shed ☐ M2 breakers open		11:10		It appeared Gen1 remained online and Gen2 tripped; B and C loads shed; isolation switch opened Gen 2 relay was reset and it

☐ ~~SDS bypass switch closed~~ ☐ ~~M1 breaker opens~~ ☐ Diesel Generator switches to isochronous mode				automatically restarted; B loads restored CES to look at PQ meter data to determine sequence of events
45A) Manually prepare system for grid reconnection ☐ Put synchronizer in manual ☐ Manually open M1 ☐ Put bypass switch in local, close bypass, put back in remote ☐ Put synchronizer in auto ☐ Put SDS in local, stop SDS, verify ISO switch opens		11:25		
46) Simulate grid restoration by reconnecting grid side voltage signal at SDS.		11:25		
47) Simulate grid restoration by reconnecting voltage signal at SEL 351 and UPC (TSM1A – G, H, I; TSM1B – G, H, I; TSUPC G, H, I). (3→1C→1)		11:25		Synchronizer did not count down; system not in auto; breaker flag needs to clear to place the allowing the system to be placed in auto before M1 can close
48) Verify M1 breaker closes to dead bus.		11:37		
49) Verify facility resynchronizes across M2 breakers		11:43		

50) Verify diesel generators turn off.		11:43		
51) Start battery in voltage source mode.		11:55		
52) Verify PV and Fuel Cell are enabled at SLC.		11:43		
53) Start SDS from SDS HMI.		12:14		Inadvertent outage while restoring SDS.
54) Verify isolation switch closes and bypass switch opens.		12:14		
LUNCH 12:00 -1:00	**12:00 P.M.**			
AND MODE TO GRID CONNECTED MODE TRANSITION TESTING (Duration ~15 Minutes) 54A) Simulate grid outage by removing grid side voltage signal. (1→2). Verify microgrid successfully islands.	**1:00 P.M.**	X		Step not required b/c this was tested earlier
54B) Open voltage signal to SEL 351 and UPC (TSM1A – G, H, I; TSM1B – G, H, I; TSUPC G, H, I).		X		Step not required b/c this was tested earlier
54C) Simulate grid restoration by reconnecting grid side voltage signal at SDS.		8:52		

54D) Simulate grid restoration by reconnecting voltage signal at SEL 351 and UPC (TSM1A – G, H, I; TSM1B – G, H, I; TSUPC G, H, I). (3→1C).		8:52		
54E) Verify SDS should closes when the voltage, frequency and phase are in windows. Record time to synchronize.		8:52		1 minute for Grid OK to sync; 1 minute to sync Jump to step 10
AND MODE TO OUTAGE MODE TO EMERGENCY MODE TRANSITION TESTING (Duration ~45 Minutes) 55) Simulate grid outage by removing grid side voltage signal. (1→2)	**1:15 P.M.**	Day 2		
56) Verify microgrid successfully islands.		Day 2		
57) Open voltage signal to SEL 351 and UPC (TSM1A – G, H, I; TSM1B – G, H, I; TSUPC G, H, I).		Day 2		
58) Verify M1 stays closed.		Day 2		
59) Simulate battery outage by simulating loss of communicatoin between emergency gen and battery GPC. The entire facility will experience an outage. This step should occur at 1:30PM. (2→4)	**1:30P.M.**	Day 2		

60) Verify the following: ☐ Battery is shutdown ☐ System is operating in Outage Mode ☐ ALL B and C loads were block shed ☐ Fuel Cell and PV are disabled ☐ M2 breakers open		Day 2		
61) Verify first diesel generator comes online and all A Loads are restored. (4→3A)		Day 2		
62) Verify second diesel generator comes online and all B loads are sequentially added in 2 second steps (3A→3)		Day 2		
IERGENCY MODE TESTING – ONE UNIT TRIP (Duration ~15 Minutes) 63) Simulate one diesel generator trip by manually shutting off generator. (3→3A)	**2:00 P.M.**	Day 2		
64) Verify B loads shed.		Day 2		
STORE SYSTEM TO NORMAL OPERATING POSITIONS (Duration ~15 Minutes) 64A) Manually prepare system for grid reconnection ☐ Put synchronizer in manual ☐ Manually open M1 ☐ Put bypass switch in local, close bypass, put back in remote	**2:15 P.M.**	Day 2		

☐ Put synchronizer in auto ☐ Put SDS in local, stop SDS, verify ISO switch opens 65) Simulate grid restoration by reconnecting voltage signal at SEL 351 and UPC (TSM1A – G, H, I; TSM1B – G, H, I; TSUPC G, H, I). (3A→1C→1)				
66) Verify M1 breaker resynchronizes to the grid.		Day 2		
67) Verify facility resynchronizes across M2 breakers.		Day 2		
68) Verify diesel generators turn off.		Day 2		
69) Start battery in DERMS mode. (1C→1)		Day 2		
~~70) Start Fuel Cell.~~		Day 2		
71) Start SDS from SDS HMI.		Day 2		
72) Put SDS in remote control.		Day 2		

PROCEDURE IS COMPLETE @ 2:30 P.M.

Full MicroGrid System Commissioning - 3/28/13 (Day 2)

DESCRIPTION:

Final commissioning of load shed system. Testing grid-connected, island, emergency and outage modes.

Yellow highlights indicate where a load shed or outage **may** occur. Red text indicates where a load shed or outage **will** occur.

RESPONSIBLE PARTIES (RP):

Chevron Energy Solutions (CES) – Jay McCaa, Eduardo Alegria

Santa Rita Jail (SRJ) – Dan Lichtenberger

Encorp – Don Clover

OUTAGE RESTORATION PLAN

1. On standby in front of generator with flashlight; Reset relay; Reset HMI alarm
2. At PCC, open M1, close bypass switch, close test switches to relay, close M1
3. BEI on standby to manually close M2

PROCEDURE	Target Start Time	Actual Start Time	RP Verification	Comments/Additional Actions Performed
1) Verify following pre-testing system conditions: ☐ Battery system is online and operating in DERMS mode. ☐ PCS is operating in voltage source mode and remote ☐ Fuel cell is ~~online~~ enabled ☐ All test switches closed at IEM panel	**10:00 A.M.**	12:30		SOC = 70% Jump to Step 26

☐ Motor pack is connected to bypass switch ☐ SLC Master Enable/Disable is ENABLED ☐ Battery SOC between 50 – 85%				
GRID MODE – LOSS OF COMMUNICATION AT PCS GPC 2) Verify bypass switch is closed and isolation switch is open.	**10:15 A.M.**	1:20		
3) Place bypass and isolation switch in remote control.		1:20		
4) Start Static Disconnect Switch (SDS) from HMI.		1:21		
5) Verify isolation switch closes and bypass switch opens.		1:21		
6) Place SDS in remote control.		1:21		
7) Remove LON connection at PCS GPC		1:27		
8) Verify following: ☐ PCS is disabled after 10 seconds ☐ SDS shuts down and bypasses itself		1:27		SDS is not able to see the command to bypass when it loses comm. Encorp to update code and retest. Code updated and tested.

ISLAND MODE – LOSS OF COMMUNICATION AT SLC TESTING 9) Start Battery PCS.	**10:45 A.M.**	1:41		
10) Start Static Disconnect Switch (SDS) from HMI.		1:42		
11) Verify isolation switch closes and bypass switch opens.		1:42		
12) Place SDS in remote control.		1:42		
13) Simulate grid outage by removing grid side voltage signal.		1:44		
14) Verify microgrid successfully islands.		1:44		Audible horn on event.
15) Open voltage signal to SEL 351 and UPC (TSM1A – G, H, I; TSM1B – G, H, I; TSUPC G, H, I).		1:44		
16) Verify M1 stays closed.		1:44		
17) In ISaGRAF, Encorp to force the battery state of charge level to 24%.		x		Step not required to test loss of comm functionality

18) Verify both diesel generators come online.		x		Step not required to test loss of comm functionality
19) Simulate loss of communication with the battery and SLC.		1:49		
20) Verify the system goes into local control and loads and Fuel Cell do not shed. Verify PV sheds.		1:49		System didn't shed PV; HU RTU went to local but SS/LS went offline; Fuel Cell did not shed; SLC was off After CES/Encorp discussion, this functionality was deemed unneeded and was removed.
21) Restore communication with battery and verify the system operating mode returns to "Island Mode" and PV is added.		1:55		
22) Restore actual battery SOC. Verify diesel generators shut down.		x		Step not required to test loss of comm functionality
23) Simulate grid restoration by reconnecting grid side voltage signal at SDS.		1:58		
24) Simulate grid restoration by reconnecting voltage signal at SEL 351 and UPC (TSM1A – G, H, I; TSM1B – G, H, I; TSUPC G, H, I). (3→1C→1)		1:58		

25) Verify SDS resynchronizes to grid.		1:59		
LUNCH	**11:30 – 12:00**			
ISLAND MODE– LOSS OF COMMUNICATION AT DIESEL GEN GPC 26) Verify SDS is closed and battery is fully available.	**12:00**	12:30		
27) Simulate grid outage by removing grid side voltage signal.		12:37		
28) Verify microgrid successfully islands.		12:37		No audible horn on event.
29) Open voltage signal to SEL 351 and UPC (TSM1A – G, H, I; TSM1B – G, H, I; TSUPC G, H, I).		12:37		
30) Verify M1 stays closed.		12:37		
31) Simulating loss of communication between emergency gen and battery GPC. This step will cause and outage and should occur at 12:30PM.	**12:30 P.M.**	12:45		Pulled comm for 4 seconds then restored to verify delay
32) Verify the following: ☐ PCS is disabled after 10 seconds ☐ System is operating in Outage Mode ☐ ALL B and C loads were block shed		12:45		

☐ Fuel Cell and PV are disabled ☐ M2 breakers open ☐ Confirm isolation switch does not open				
33) Verify first diesel generator comes online and all A Loads are restored. (4→3A)		12:45		
34) Verify second diesel generator comes online and all B loads are sequentially added in 2 second steps (3A→3)		12:45		
IERGENCY MODE TESTING – ONE UNIT TRIP 35) Simulate one diesel generator trip by manually shutting off generator. (3→3A)	**1:00 P.M.**	12:52		
36) Verify B loads shed.		12:52		
STORE SYSTEM TO NORMAL OPERATING POSITIONS 37) Manually prepare system for grid reconnection ☐ Put synchronizer in manual ☐ Manually open M1 ☐ Put bypass switch in local, close bypass, put back in remote ☐ Reset breaker by turning the breaker to the close position. Verify red flag on control switch. ☐ Put synchronizer in auto ☐ Clear relay targets	**1:15 P.M.**	12:56		

☐ Put SDS in local, stop SDS, verify ISO switch opens				
38) Simulate grid restoration by reconnecting grid side voltage signal at SDS.		12:57		
39) Simulate grid restoration by reconnecting voltage signal at SEL 351 and UPC (TSM1A – G, H, I; TSM1B – G, H, I; TSUPC G, H, I). (3→1C→1)		12:57		
40) Verify M1 breaker closes to dead bus.		12:58		
41) Verify facility resynchronizes across M2 breakers		1:04		
42) Verify diesel generators turn off.		1:04		Jump to Step 2
43) Start battery in DERMS mode. (1C→1)				
44) Start Fuel Cell.				
45) Start SDS from SDS HMI.				
46) Put SDS in remote control.				

PROCEDURE IS COMPLETE @ 1:30 P.M.