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(EW-201245)

Distributed Storage Inverter and Legacy Generator Integration Plus Renewables Solution for Microgrids

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6. AUTHOR(S)
Mr. Slobodan (Bob) Krstic
Mr. Tom Pier

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Eaton Corporation
W126N7250 Flint Drive
DBA INNOVATION CENTER
Menomonee Falls, WI 53051-4404

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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Environmental Security Technology Certification Program
4800 Mark Center Drive
Suite 17D03
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The objectives of this project were to demonstrate the ability to operate a microgrid with less expensive power storage instead of large scale energy storage and that the renewable energy with small-scale power storage can maintain power quality in islanded mode with minimal use of the generators during non-optimal (e.g. cloud covered) periods. A 400kW microgrid application employing power optimized energy storage, transient rated storage inverter, microgrid enabled PV inverters, relatively high percentage PV energy source component as well as modified legacy natural gas (NG) generator control were successfully demonstrated. The demonstrations showed that power optimized, in conjunction with NG generators and renewables, can support an islanded microgrid without loss of power quality, staying within per IEEE-STD-1547 voltage and frequency limits. This includes the case an unintentional island, where grid is lost and generators were off. The demonstrations also showed that high penetration PV along with power optimized storage can power an islanded microgrid, and supplement generators while maintaining a stable voltage bus.

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ACRONYMS AND ABBREVIATIONS

BMS	Battery Management System
CEP	Central Energy Plant
CERL	Construction Engineering Research Laboratory
CO_2	carbon dioxide
DC	direct current
DoD	Department of Defense
DPW	Department of Public Works
Eaton	Eaton Corporation
EO	Executive Order
ESTCP	Environmental Security Technology Certification Program
GHG	greenhouse gas
HP	horsepower
HVAC	heating, ventilation, and air-conditioning
Hz	hertz
IAPS	Integrated Alternative Power Systems
IEEE	Institute of Electrical and Electronics Engineers
ISO	industry standard object
JBPHH	Joint Base Pearl Harbor Hickam
kVA	kilo volt-amperes
kVAR	Kilo Volt-Amperes Reactive
kW	kilowatt
kWHr	kilowatt hour
Li Ion	lithium ion
MCAS	Marine Corps Air Station
MCB	Marine Corps Base
MW	megawatt
NAVFAC	Naval Facilities Engineering Command
NG	natural gas
nLTO	Lithium-Titanate Oxide
NSWC Crane	Crane Division, Naval Surface Warfare Center

ACRONYMS AND ABBREVIATIONS (continued)

PO	performance objectives
POC	point of contact
PQ	Power Quality
PV	photovoltaic
SOC	state of charge
the Plan	Strategic Sustainability Performance Plan
V	volt
ZBB	ZBB Energy Corporation

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EXECUTIVE SUMMARY

Current microgrid designs integrating distributed generation and renewable energy sources require large scale energy storage, typically in the form of batteries, to enable a high power quality transition to islanding. These energy storage systems, however, are prohibitively expensive and will slow the application of microgrids at U.S. installations. The Eaton solution replaces these oversized and expensive systems with a power storage approach at lower cost and comparable performance.

OBJECTIVES OF THE DEMONSTRATION

The project had two main objectives:

1. Demonstrate the ability to operate a microgrid with less expensive power storage instead of large scale energy storage.
2. Demonstrate that the renewable energy with small-scale power storage can maintain power quality in islanded mode with minimal use of the generators during non-optimal (e.g., cloud covered) periods.

TECHNOLOGY DESCRIPTION

This project's solution is a power optimized storage approach to microgrids that replaces today's approach of long term energy storage with (legacy) generators primarily off-line and intermittent renewable sources like photovoltaic (PV). The technologies employed in this solution are power delivery optimized storage, transiently rated inverters, integration with legacy generator controls, and microgrid compatible inverters for PV.

A 400 kilowatt (kW) microgrid application employing power optimized energy storage, transient rated storage inverter, microgrid enabled PV inverters, and a relatively high percentage PV energy source component as well as modified legacy natural gas (NG) generator control was successfully demonstrated. The microgrid load and some of its auxiliary equipment is an air conditioning chiller, presenting a variable load up to 350kW. Figure ES1 depicts the major components of the power optimized microgrid and the associated three phase power connection scheme.

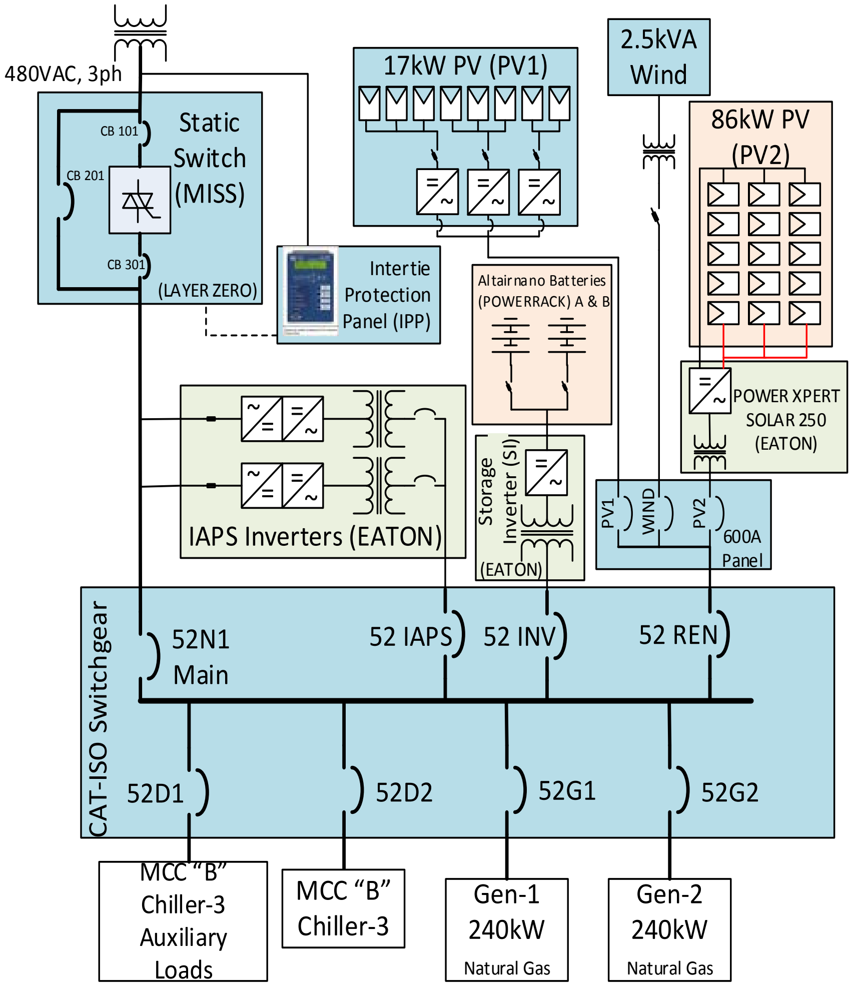

Figure ES1. Fort Sill microgrid system one line diagram.

DEMONSTRATION RESULTS

The demonstrations were successful and showed that power optimized storage, in conjunction with NG generators and renewables, can support an islanded microgrid without loss of power quality, staying within Institute of Electrical and Electronics Engineers (IEEE) Standard 1547 voltage and frequency limits. This includes the case of an unintentional island, where grid is lost and generators were off. The storage system powers the load until generators go online, with generator synchronization being faster due to the stable bus provided by the storage system. The demonstrations also showed that high penetration PV along with power optimized storage can power an islanded microgrid, and supplement generators while maintaining a stable voltage bus.

Compared to energy optimized storage, the power optimized storage system proved to be 33% of the cost and 13% of the physical volume. This will enable greater acceptance and penetration of microgrids, as energy storage is typically the most costly required new equipment for a high performance microgrid.

IMPLEMENTATION ISSUES (Lessons Learned)

- The power optimized energy storage has a significantly smaller footprint; this provides future owners greater flexibility in storage system installation location.
- For large inductive loads, reduced voltage starting techniques should be used where possible, to reduce transients within the power system and maintain line voltage above IEEE 1547 minimums.
- Any future operators must be identified early in the deployment process so that they acquire a more complete understanding of the technology, its intended use, and future maintenance issues.
- When using parallel racks of batteries, isolating a “bad” rack is more efficient than keeping it in the microgrid, as the Battery Management System (BMS) calculation of state of charge (SOC) is based on all the racks.

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1.0 INTRODUCTION

Current microgrid designs integrating distributed generation and renewable energy sources require large scale energy storage, typically in the form of batteries, to enable a high power quality transition to islanding. These energy storage systems, however, are prohibitively expensive and will slow the application of microgrids at U.S. installations. The Eaton solution replaces these oversized and expensive systems with a power storage approach at lower cost and comparable performance.

This project had two main objectives:

1. Demonstrate the ability to operate a microgrid with less expensive power storage instead of large scale energy storage; and
2. Demonstrate that the renewable energy with small-scale power storage can maintain power quality in islanded mode with minimal use of the generators during non-optimal (e.g., cloud covered) periods.

1.1 BACKGROUND

Currently, microgrids for energy surety use centralized large energy storage systems at high costs because diesel and gas generators cannot support the transition to islanding. Rotating reserve also might be able to provide this “storage,” but it is undesirable as it requires inefficient 24-hour operation of generators and has a single point of failure. The solution demonstrated uses power optimized energy storage modules; these are co-located and integrated with the distributed generators. This integrated storage generator system has the benefits of minimum battery size and cost (requiring only 1 minute of storage to bridge the time for a generator to parallel with the microgrid); allows the application of a small and lower cost transient rated inverter (advantage of short term storage); and enables microgrid upgrade of legacy generator assets (integration of inverter and generator controllers). This solution reduces storage costs by 67%, with a large increase in reliability (see Performance Objective “Procurement Cost Reduction of Storage” in Section 3.1). The storage inverter and hardware are also leveraged to provide an islanding inverter (microgrid compatibility) for renewable energy sources (photovoltaic [PV] for this program), which maximizes the effective load carrying capacity of the renewable energy source when grid connected or islanded, and reduces generator fuel consumption.

1.2 OBJECTIVES OF THE DEMONSTRATION

The first objective of the project is to demonstrate the ability to operate a microgrid with natural gas (NG) generators without large scale battery energy storage. A power storage system (with approximately 1 minute of capacity) enables the generators to rapidly synchronize to the inverter and power the islanded microgrid; support grid stability by providing transient power (real and reactive); and support PV power transitions to maintain a stable islanded microgrid.

The second objective of the demonstration is to show that the renewable energy can maintain power quality in islanded mode with minimal use of the generators during non-optimal (e.g., cloud covered) periods. The demonstration features a large (relative to the overall system power requirements) PV solar array, whose inverter is configured to provide generator like operation, including volt-ampere reactive (VAR) support (reactive power) for microgrid voltage stability.

1.3 REGULATORY DRIVERS

The demonstrations showed technologies that enable stable operation of microgrids with a high penetration of renewables (in this case PV), and lower cost energy surety by using power optimized storage.

The Department of Defense (DoD) Strategic Sustainability Performance Plan (the Plan) specifically calls out the following mandates:

- Executive Order (EO) 13514: Articulates both general and specific requirements to improve Federal government efficiency through the development of a green economy and a decreased dependence on fossil fuels. The Plan provides a coherent approach both for complying with multiple Federal requirements for sustainability and for assuring the mission. The linkages between sustainability and the DoD mission are strong and direct. There are four key areas of intersection that form priorities for DoD:
    1) Energy and reliance on fossil fuels;
    2) Chemicals of environmental concern;
    3) Water resources management; and
    4) Maintaining readiness in the face of climate change.

- EOs 13423 & 13514: ‘‘Sustainability” and “sustainable’’ mean to create and maintain conditions, under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic, and other requirements of present and future generations of Americans. In January 2010, DoD released an aggressive target under EO 13514 for reducing direct greenhouse gas (GHG) emissions from facilities and non-tactical fleet vehicles. These emissions are due to direct energy use, especially electricity.

The technologies demonstrated microgrid operation with less generator run time, and lower fuel consumption due to the contribution of the system’s PV. This results in lower emissions and GHGs.

2.0 TECHNOLOGY DESCRIPTION

This project's proposed solution is a power optimized storage approach to microgrids that replaces the current method of long term energy storage with (legacy) generators that are primarily off-line and intermittent renewable sources like PV. The technologies employed in this solution are power delivery optimized storage, transiently rated inverters, integration with legacy generator controls, and microgrid compatible inverters for PV.

2.1 TECHNOLOGY OVERVIEW

2.1.1 Performance of Natural Gas Generators in Microgrid Applications

NG generators are well suited for modern microgrids because of their low emissions and cost. However, NG generators (and modern diesel generators meeting emissions requirements) cannot synchronize quickly, connect to other online generators, or respond to fast load transients. Because microgrids will likely be formed out of existing legacy generators that could be of different sizes and different fuel types, addressing these transients is critical [1]. The response of NG engines pose a problem when operating in a microgrid with diesel engines and inverter based renewables when the frequency and voltage are not stable. The second or third generator that has to come on-line takes time to synchronize to the fluctuating frequency and voltage from the generators already online.

2.1.2 Performance of Renewables in Microgrid Applications

Renewable energy sources such as Solar PV, Solar Thermal, and Wind are seen to be important for energy surety of military posts and other critical facilities. However, all renewables are intermittent by nature and their energy output cannot be forecasted. To address the gap between the availability of these sources and the demand, several studies have proposed large energy storage to fill the energy, but the size and cost of the large centralized energy storage is cost prohibitive for an economical microgrid solution. An alternative to large energy storage batteries powered with large energy storage inverters is demonstrated here. Typically, a NG or diesel generator is present in the microgrid energy sources and the need for battery energy storage can be met with these generators if the transient capabilities of the generators are managed. The transients are typically of short durations (tens of seconds), and can be managed with the planned microgrid enabled controls.

2.1.3 Transient Rated Inverter

As seen in Figure 1, in a distribution system when the microgrid is islanded by opening the upstream static switch, the inverter with power storage supports the load, adds system stability and transfers it to the generator(s). This smooth transfer enables other generators to connect to the microgrid as the frequency and voltage swings are managed. These generators can synchronize simultaneously (rather than sequentially over a longer time, as presently done). Given this stable microgrid voltage, frequency and rapid synchronization, the time (and energy) to support the load is shown to be small, less than 1 minute (even for NG generators).

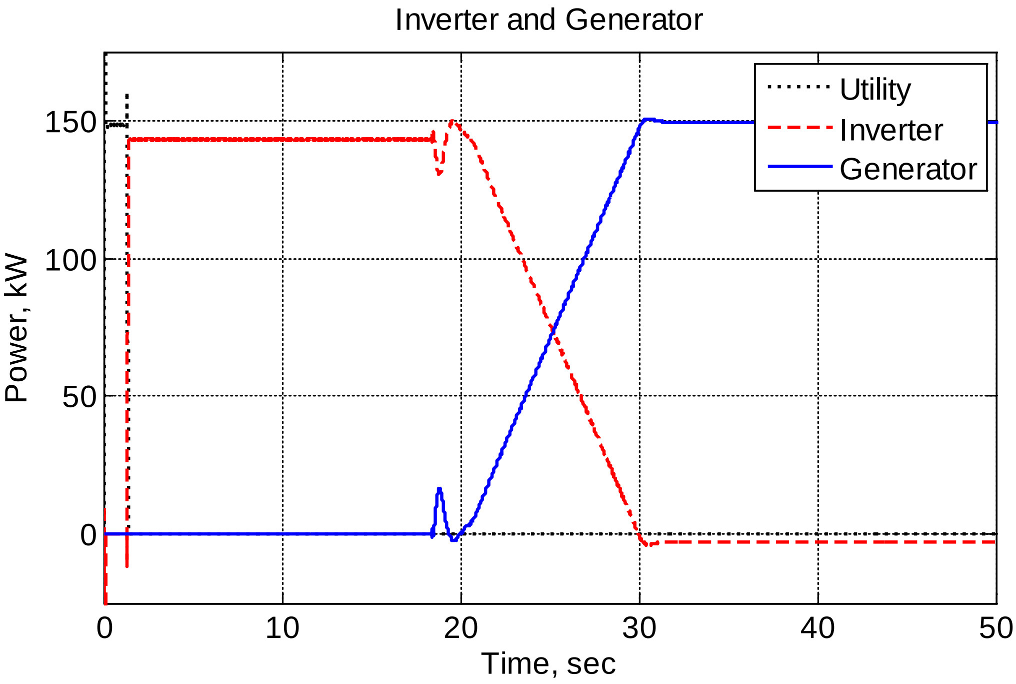

Figure 1. Power during utility generator transition.

A further application of the inverter is to upgrade the generator controls for microgrid capability (e.g., shared data with inverter, and genset P and Q dispatching). Legacy generators do not typically provide this microgrid compatible performance since they do not have the communication. The inverter will communicate with the microgrid and modify the behavior of the legacy generator to mimic a microgrid compatible generator. As such, the inverter will provide the transient power and the legacy generator will not need the performance enhancements.

Because the required short-time energy storage is small and can be integrated with the generator, a legacy generator can maintain a microgrid by leveraging the inverter with energy storage to support the load during the synchronization process. The inverter only needs to support the microgrid in small intervals, therefore, commercial scale inverters can be used but at a higher rating. These inverters can be used with minor modifications in their switching algorithms and thermal design to meet the short term needs. The inverters are then smaller and cheaper. For this project's demonstration, a fully rated inverter will be used (reuse of an existing storage inverter to reduce project costs). Future installation can take advantage of lower rated inverters (a low risk technology).

2.1.4 Power Optimized Energy Storage

The energy storage system implemented was a nano Lithium-Titanate Oxide (nLTO) system from Altairnano. This newer form of lithium-ion battery technology replaced the traditional graphite anode with a nanostructure Lithium-Titanate formula ($Li_4Ti_5O_{12}$). The cathode is Lithium Cobalt Nickel Manganese Oxide ($LiCo_xNi_yMn_zO_2$).

The complete battery system utilizing the nLTO cells is housed within two rack assemblies (Figure 6). Each rack assembly consists of two battery cabinets and an electronics cabinet that controls the power. This system includes two strings of 20 (40 total) 24 volt (V) modules using 60 Ah cells wired in series. The system voltage is 360 V to 550 V.

2.1.4.1 Comparison to Existing Technology

The Altairnano nLTO cell technology produces distinctive performance attributes, including extremely fast charge and discharge rates, the industry's highest round-trip efficiencies, long cycle life, improved safety, and the ability to operate under diverse environmental and thermal conditions.

2.1.4.2 Chronological Summary

The Altairnano technology is built upon proprietary advanced materials acquired from BHP Minerals International, Inc. in 1999. Altairnano continued to expand and refine various applications of the material technology. Today, the technology is used to produce various nano-sized powders, cells, and assembled battery modules that have current or potential applications within the energy sector.

2.1.4.3 Future Potential for DoD and Anecdotal Observation

Altairnano performed high-rate overcharge, puncture, crush, drop, and other comparative tests in accordance with United Nations/Department of Transportation and Military 810 test procedures with no explosions or safety concerns exhibited by the nLTO cells.

Crane Division, Naval Surface Warfare Center (NSWC Crane) Test & Evaluation Branch (Code GXSM) was tasked by Altairnano to perform safety abuse testing on Lithium Nano-Scale Titanate Oxide cells and modules. Detailed results are reported in Crane Document Number: GDD GXS 11-053 (Preliminary Report) Issue Date: 05/3/2011.

2.1.5 PV Inverter with Microgrid Controls

Existing PV inverters with Institute of Electrical and Electronics Engineers (IEEE) 1547 controls go offline on a utility outage or on a power quality event and will not support the microgrid. The control strategy used in the power storage inverter for converting legacy generators to microgrid compatible ones is applied to these PV inverters also. This will enable the PV energy source to be utilized in the microgrid as the prime source, to aid microgrid stability, and can further be integrated with the distributed power storage to address intermittent loss of PV energy as when a cloud passes over the PV array. This minimizes generator run time and offsets the required generator installed capacity (for islanding) based upon the PV electrical load carrying capacity.

2.2 TECHNOLOGY DEVELOPMENT

The bulk of the technology development was the integration of diverse equipment onto a microgrid capable control system. This system was based on an existing switchboard/generator control system (per CAT-ISO) with software modifications for storage inverter integration, and coordinated operation of sources. Modification of PV inverter for microgrid operation was also a software and integration effort. Descriptions and examples of this integration are given in Sections 4, 5, and 6.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

2.3.1 Primary Benefits

The technology solution demonstrated provides a commercial path for converting existing distribution systems into microgrid capable systems without the high cost of grid scale energy storage. The solution achieves energy surety and security, high power quality, ride-through, fast-acting transient real and reactive power support and will enable islanding of microgrids. The power optimized energy storage and inverter used is commercial off-the-shelf technology and is approximately 33% of the cost of typical utility scale battery energy storage solutions deployed today. The storage inverter controls and hardware were leveraged to provide an islanding inverter (microgrid compatibility) for renewable energy sources (PV for this program), to maximize the effective load carrying capacity of the renewable energy source when grid connected or islanded.

2.3.2 Storage Technology Progression

While lithium ion (Li-Ion) batteries are the present, preferred choice (and planned for the demonstration), Eaton expects to ultimately transition to capacitor-based storage for transient rated applications, as this technology is expected to become dominant for short duration high power applications as costs continue to decline. A key aspect to the Eaton power storage approach is that the short duration times enable an open architecture approach to storage technology, as both batteries and capacitors are possible, given the proper integrated system controls (that will be demonstrated).

2.3.3 Reduced Ability to Perform Load Shifting

A primary focus of this project was to demonstrate a reduction in energy storage (and its cost) while maintaining power surety. As such, load shifting (storing excess renewable energy for time shifted use when renewable power is not available) did not occur to a significant extent using the power optimized batteries (for this project). Instead the bulk of the renewable energy will immediately be consumed (within the microgrid) or exported to the utility. For the islanded microgrid case, the NG generators were used to provide power. The proposed power optimized storage concept is not incompatible with load shifting, but it is not optimized for it.

This approach (immediately consuming renewables and using generators, as needed, when islanded) can be shown to be a more cost effective method than time shifting the renewable energy. The payback time for time shifting is very long given the high cost of bulk energy storage, and low cost of utility power. For example, the energy optimized ZBB system can store 500 kilowatt hours (kWHr) of PV energy for use at night. Assuming an energy cost of $0.12/kWHr, the result is $60 of energy per night. Given the cost of the ZBB system, the payback time is 27 years.

2.3.4 High Inrush Loads

As the primary large load on the microgrid, the chiller induction motor presented operational challenges as it was a very high inrush current load on startup, since it used a Wye-Delta starter.

Replacing that starter with a soft starter or variable speed drive would have reduced the peak currents and improved chiller start operation when islanded. Unfortunately, the starter replacement was not an option at this site as permission to change chiller load system was not received. In future installations, optimizing the control of motor loads is recommended.

2.3.5 Generator Run Time

At the Fort Sill site, restrictions on generator run time limited the duration of islanded operation; hence microgrid effectiveness. While the power optimized storage technical approach is sound, it does require the ability to run generators as needed for islanded operation. Treating the generators as emergency backup class devices was a limitation on microgrid effectiveness.

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3.0 PERFORMANCE OBJECTIVES

This section describes the technology and economic performance objectives (PO) that were successfully demonstrated. These objectives will show the contribution of this technology to DoD Energy and Water goals for Energy Security and Cost Avoidance for military installations.

- Energy and Water Security: The demonstration performance objectives show that power optimized storage is suitable for military microgrid applications in terms of stabilizing the islanded microgrid bus voltage, supporting loads, and enabling faster generator synchronization. The objectives will also show that high penetration PV can be enabled to support islanded microgrid buses and variable loads.
- Cost Avoidance: The demonstration performance objectives show that power optimized storage is suitable for military microgrid applications, and that such storage systems have a significantly lower procurement cost than typical energy optimized storage systems used in utility and microgrids installations.

The Eaton team collected data during system operation to evaluate the technical objectives of the project. A summary of project performance objectives is provided in the quantitative performance objectives table below. Demonstration results are summarized in Section 6.

Table 1. Performance objectives.

Performance Objective	Metric	Data Requirements	Success Criteria
Quantitative Performance Objectives:			
Demonstration 1 Load support with rapid generator synchronization	Seconds	Microgrid voltage and frequency measurement. Generator, storage inverter output power measurements. Load power measurements.	Synchronization of both generators with no loss of microgrid loads.
Demonstration 2 Load step support to recover voltage and frequency	kW, kVARs, Vs, Hz, Seconds	Microgrid voltage and frequency measurement and time to recover from a step load.	Load step voltage and frequency recovery improved by 50%. Comparing case with and without storage system.
Demonstration 3 Storage powering of microgrid without generators	kW, kVARs, Vs, Hz	Load voltage and frequency measurement.	>45 seconds of islanded microgrid power without loss of power quality to loads (60% of storage rated power).
Demonstration 4 Quantify fuel savings given PV for islanded operation	NG fuel use (cubic feet)	Estimated fuel consumption as derived from generator run time and load level	Actual field data that quantifies fuel savings given high penetration PV. Condition 1: Running operation without PV. Condition 2: with PV active.
Demonstration 5 PV + Storage support managing variable loads	kW, kVARs, Vs, Hz	Microgrid voltage and frequency measurement. Microgrid load power measurements. PV system output power measurement.	Load step of 50% of available PV with stable microgrid bus, with no generators on line and above 30% PV rated power available.
Demonstration 6 PV + Storage support managing variable solar	kW, kVARs, Vs, Hz	Microgrid voltage and frequency measurement. Microgrid load power measurements. PV system output power measurement.	In a solar day with the load less than 50% of average available PV, microgrid bus will remain stable, with no generators on line.
Demonstration 7 Procurement cost reduction of storage	$	Production costs of storage systems	67% reduction of procurement cost of storage system
monstration 8 Smaller footprint for storage	Square feet (area)	Floor space required for storage systems	50% reduction of storage system footprint
Demonstration 9 Ramp rate control of PV power transitions with support from energy storage	kW, kVARs, Vs, Hz, seconds	Microgrid voltage and frequency measurement. Microgrid load power measurements. PV DC power measurement. Storage inverter output measurement.	60 second effective ramp down of power given PV reduction (due to cloud passing overhead). With and without ramp rate control enabled, collect data over typical solar days.
Demonstration 10 High penetration PV and control of PV power ramp rate for generator stability	kW, kVARs, Vs, Hz, seconds	Microgrid voltage and frequency measurement. Microgrid load power measurements. PV DC power measurement, storage inverter and generator output measurement.	Generator output voltage stability given a 60% PV DC power step (up or down). Stability is defined as voltage maintained within +10%/-12%, and frequency within 60.3Hz/59.3Hz.
Demonstration 11 Microgrid voltage support from PV inverter	kVARs, Vs, seconds	Microgrid voltage measurement. Microgrid load kVAR measurements. PV inverter kVAR measurements.	125 kVAR contribution by PV inverter during a reactive load step.

Demonstration 12 Validate/Quantify storage needs – peak power and time duration	Power output and cycle count	Storage system power output profile (Peak Power and time duration) over extended operating period.	Actual field data that quantifies storage need based on microgrid capacity. Condition 1: 1 month of free running operation. Condition 2: 1 month with an added variable load that emulates the worst case load profile seen during condition 1.
Demonstration 13 Assessment of application areas within DoD infrastructure	DoD Sites, MW	DoD site power system data, power (profile) needs, and energy security requirements.	50 MW of potential DoD application areas identified having strategic mission significance.

Hz = hertz
DC = direct current
kVAR = kilo volt-amperes reactive
kW = kilowatt
MW = megawatt

4.0 SITE DESCRIPTION

The Fort Sill military base is located in the southwestern region of Oklahoma, approximately 80 miles (130 km) southwest of Oklahoma City. Fort Sill weather is typical of the southwest with high summer temperatures and the potential for low winter temperatures. It is also in the path of severe storms during spring and early summer. These conditions made for a good location to test the ability of microgrid equipment to operate in the climate extremes and for this equipment to provide energy surety during severe weather conditions.

Facility Criteria

This project involved the Central Energy Plant (CEP) Building 5900, located on Francis Street at Fort Sill, Oklahoma. The CEP provides the cooling needs of the five Starship training buildings in the vicinity. It is a specific chiller (designated as #3) in this overall CEP cooling system that is included in the microgrid central to this demonstration. The operation of this chiller will allow the critical systems of one or more Starships to be operable during utility power outages.

Facility Representativeness

The microgrid demonstration was specified and designed to be a small (~400 kW) representative example of future energy surety installations. Building 5900 and the chiller loads represent a broad based representative example for a number of reasons including:

- The CEP cooling system operation is considered essential to the continuation of the Starship training activities.
- The operation of the chiller system represents a particularly difficult load to start and manage; therefore it represents a “worst case” test for the microgrid system.
- The microgrid system integrates a wider variety of distributed generation sources, including natural gas generators, solar PV installations, wind installation, and an energy storage system.
- Building 5900, the CEP cooling system are part of a larger and longer term vision of being able to island all the substation feeder that they are part of. This project can be seen as a one of the first steps in achieving this vision.

Given the high power loads included in this demonstration, how it is incorporated into the larger power system of CEP Building 5900, and how this system fits into the larger ‘feeder based’ microgrid plans for Fort Sill, it will be possible to replicate and expand upon this technical work and overall design at virtually any military base.

4.1 FACILITY/SITE LOCATION AND OPERATIONS

- *Demonstration Site Descriptions:* Fort Sill is a U.S. Army post in Lawton, Oklahoma, about 85 miles southwest of Oklahoma City.
- *Key Operations:* Fort Sill serves as home of the U.S. Army Field Artillery School as well as the Marine Corps’ site for Field Artillery Military Occupational Specialty School; U.S.

Army Air Defense Artillery School; the 31st Air Defense Artillery Brigade; the 75th Fires Brigade; and the 214th Fires Brigade. Fort Sill is also one of the five locations for Army Basic Combat Training. The five Starship training facilities that are provided cooling water from the CEP Building 5900, are central to meeting the training mission of this military base.

- *Command Support:* Fort Sill supports the Eaton /ESTCP demonstration on the DoD facility. The point of contact (POC) for the Fort Sill facility was Mr. Christopher Brown, Energy Manager. Fort Sill provided a letter of support that was submitted at the proposal stage of this program and he continued to stay closely connected with the microgrid projects.
- *Location/Site Map:* This project expanded the original microgrid demonstration system by adding more PV, and replacing the existing batteries with a power optimized battery system. The location of the new PV array and PV inverter is shown in Figure 2. The location inside building 5900 of the new battery system and relocated storage inverter is shown in Figure 3.

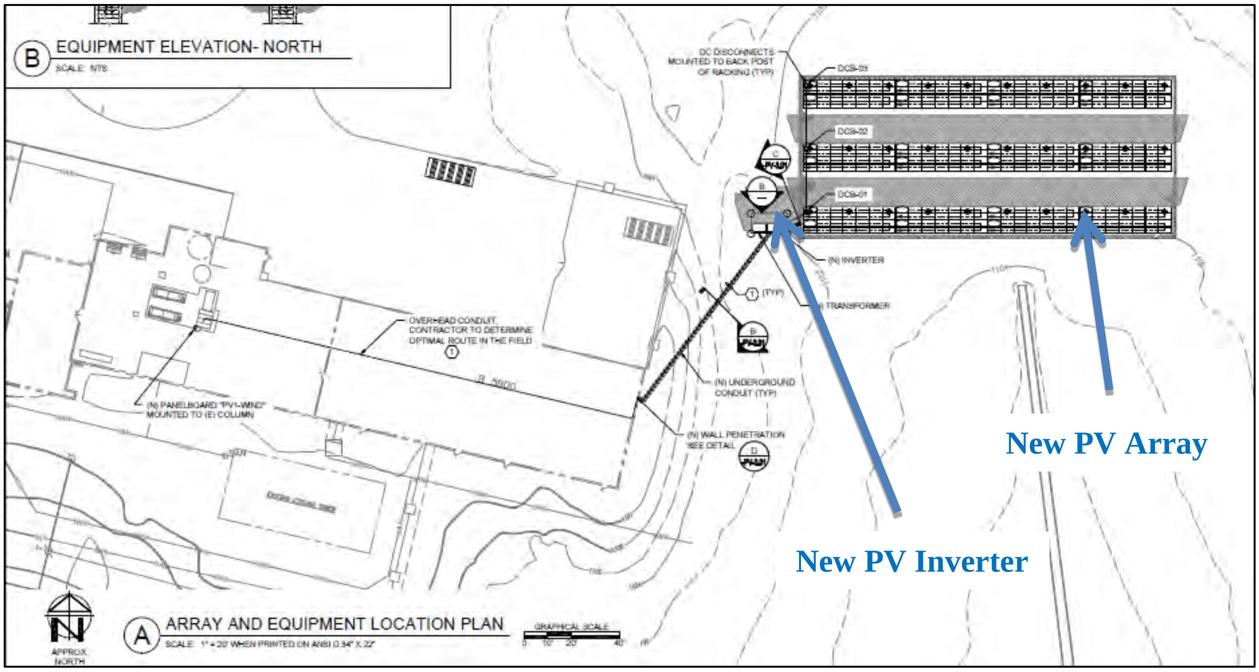

Figure 2. New PV array and PV inverter location.

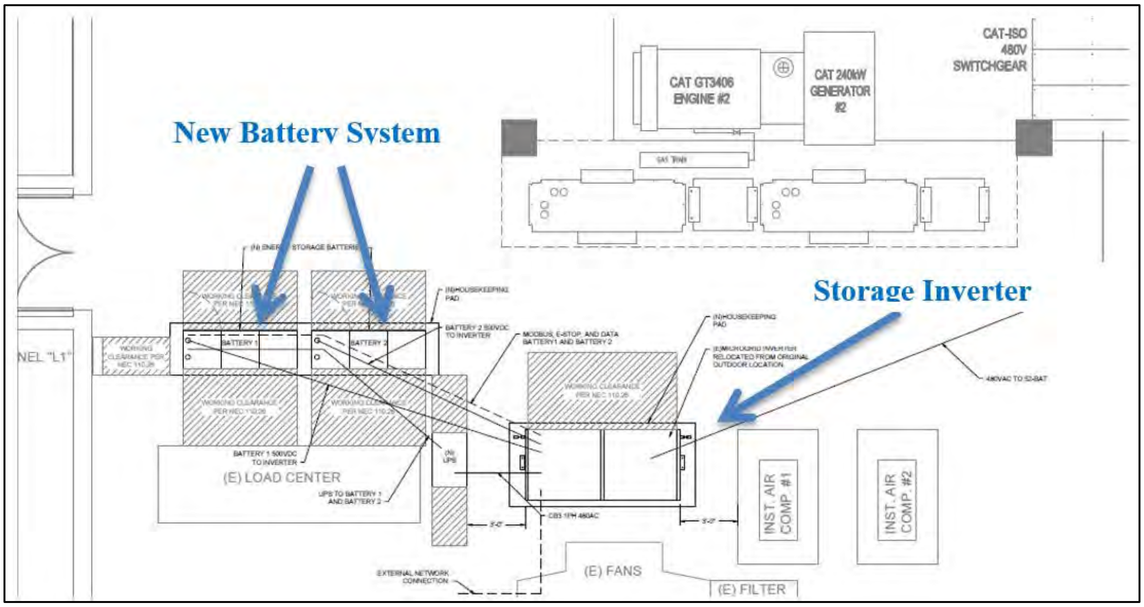

Figure 3. Storage inverter and batteries located Building 5900.

A one-line diagram of the microgrid is shown in Figure 4. The items in red are changes, with blue items being added by this project to the existing microgrid.

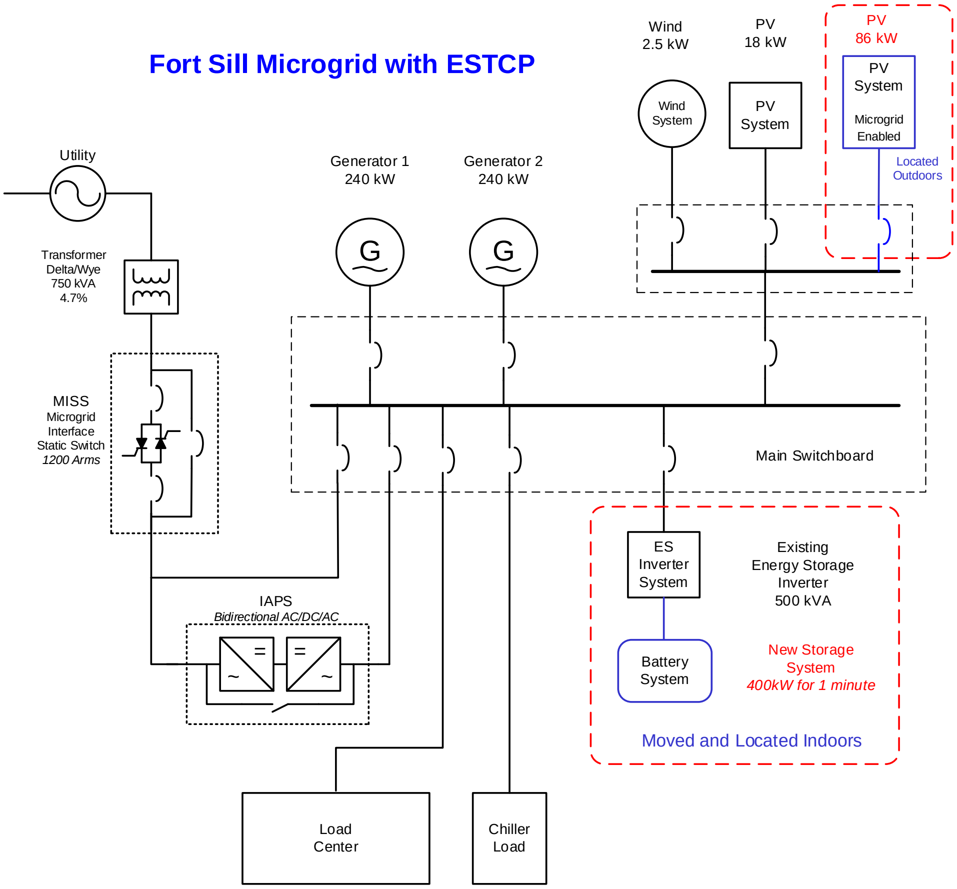

Figure 4. Fort Sill microgrid with ESTCP project additions.

4.2 FACILITY/SITE CONDITIONS

Site conditions are described above.

5.0 TEST DESIGN

This section provides a description of the system design and testing procedure to address the performance objectives described in Section 3.0.

5.1 CONCEPTUAL TEST DESIGN

- *Hypothesis:* The hypothesis is that power optimized storage can support the microgrid to maintain power quality given generator response limitations, and PV power limitations. Also, PV with microgrid controls in conjunction with storage can maintain microgrid power with minimal use of generators.
- *Test Design:* The tests were designed to obtain the data for each performance objective described in Section 3. The microgrid voltage and frequency were monitored and recorded for power quality, as were the output levels (kW and KVAR) of the storage, PV, and generator sources. Loads were stepped on/off (as described) or held constant as needed. The battery state of charge (SOC) was monitored. Battery support of generator tests was also done with a reduced battery capacity to aid in quantifying how much battery power is needed for a given generator rating to obtain the desired performance objectives. Similar reduced battery capacity testing will be done for PV related tests.
- *Test Phases:* The testing phases consisted of commissioning the updated storage system and the new PV system, and then performing the demonstrations.

5.2 BASELINE CHARACTERIZATION

- *Reference Conditions:* The baseline conditions that were measured are generator synchronization time; generator response time to load steps; generator fuel use (estimated given load and efficiency curves); chiller load inrush kVAR demand at startup; microgrid (islanded) steady state power quality; utility steady state power quality; and storage battery charge/discharge time and energy (SOC: 30%-to-90%, 90%-to-30%) at full power. The generators were warmed up by running them for 20 minutes. For PV related tests, the load was selected based on the typical PV power availability.
- *Microgrid Load Availability:* The designated load for the microgrid is Chiller #3 in the 5900 Francis Street Building. For much of the data collection period, Chiller #3 was non-operational due to the failure of a pump associated with the chiller. This pump was not repaired (by Fort Sill personnel) until late May 2014. As a result, it was necessary to load the microgrid with resistive loads, which were connected at each of the Integrated Alternative Power Systems (IAPS) inverters. All tests prior to June 2014 made use of these resistive loads.
- *Data Collection Equipment:* For collecting the data, a Fluke 1750 was connected to the IAPS breaker to monitor the voltage, current, frequency, and phase of the microgrid output to the resistive loads. A “Red Lion” data collection device within the CAT-ISO provides a time stamped record of the root mean squared (RMS) voltage, current, frequency, kW and kVAR of the microgrid in an islanded condition. Data samples are taken every 2 seconds. The Solar radiation will be tracked during the day to correlate the Effective Load Carrying Capacity (ELCC) of the array for the days the data was collected

to the load that was connected to the system. An Eaton PXM2000 energy meter is embedded in the solar inverter and maintains a 90-day record of the inverter output.

5.3 DESIGN AND LAYOUT OF SYSTEM COMPONENTS

- *System Design:* The overall system is a low voltage microgrid with several internal sources, storage, renewables, and a few large loads. The power optimized battery system is commercially available (from Altairnano). The PV array is standard commercial equipment, while the PV inverter is a standard Eaton unit with a control interface allowing for microgrid enabled performance.
- *System Depiction:* The full Fort Sill microgrid system is shown in Figure 4. The items being added for this demonstration project are the expanded PV system and the power optimized battery system. An existing storage inverter was reused for the power optimized battery system.
- *Components of the System:* The main elements of the microgrid system are the following:
    - Microgrid interface static switch: This is a fast (sub-cycle) switch for rapidly disconnecting the microgrid from the utility.
    - NG generators: These are two Caterpillar (CAT) NG generators (240 kW) intended for emergency backup power. They are used as power sources when islanded as needed for the demonstration.
    - Windmill: A small 2.5 kW rated windmill is a renewable source within the microgrid.
    - Existing PV: A standard 17 kW PV system is a renewable source that existed within the microgrid prior to this project.
    - 86kW PV system: This microgrid enabled PV system (as shown in Figure 5) was added for the demonstration of high penetration PV within microgrids. The PV inverter has a 250 kW rating, which provides capacity for kVAR support. If the PV inverter is islanded with no other source present (no generators or storage inverter) it will shut down for at least 5 minutes (per IEEE 1547, anti-islanding). It will then try to reconnect, if the utility or a local microgrid source (generators or storage inverter) is present.

Figure 5. 86kW PV array and PV inverter.

    - Storage system: The power optimized storage system is composed of a 400 kW (two parallel 200 kW units) battery system having a 56 kW/hour total capacity, as shown in Figure 6. The storage inverter is a 500 kilo volt-amperes (kVA) rating unit (shown in Figure 7) intended for a prior microgrid demonstration (with a flow battery system). The storage inverter keeps the frequency and voltage within limits to prevent the PV inverter from sensing that the system is operating in an islanded manner.

Figure 6. 400kW power optimized storage battery.

Figure 7. 500kW storage inverter.

  - IAPS: a system intended to demonstrate interconnection of microgrids and utilities with different frequencies (non-synchronized). For this demonstration project, IAPS will serve as a resistive load tie point.
  - Chiller and auxiliary loads: The primary microgrid load is a chiller driven by a 400 horsepower (HP) induction motor. The measured full load input is 214 kW, 182 kVARs, 339 amps. The chiller load can be controlled by the automation system. Other loads are present to support the chiller and its processes, and include chilled water loop pump, chilled water process pump, and air compressors.
  - Microgrid monitoring units: Two monitoring units are present in the system: 1) storage inverter output; and 2) IAPS microgrid output. These units monitor voltage and current.
- *System Integration:* The existing Fort Sill microgrid was demonstrated and proven prior to the start of this project's demonstration testing. The added PV connects directly to the existing PV/wind switchboard input, and its integration is mainly an expansion of capacity. The battery system uses the existing storage inverter and the same switchboard interface, so its integration is mainly an update of controls based on the new battery performance ratings.
- *System Controls:* The existing microgrid control system is based on industry standard object (ISO) Electronic Modular Control Panel (EMCP) 3.S controllers. Four controllers are networked and manage the system. The controllers are assigned to: 1) Utility Interface (Microgrid Interface Static Switch); 2) Generator #1; 3) Generator #2; and 4) Storage Inverter. In addition, controller #1 also monitors the IAPS unit resistive load, while controller #4 monitors the PV/Wind output. In addition to managing microgrid modes, this system enables sharing of source/load data between all the microgrid sources. This enables optimization of controllable PV output, and storage system response within limits on communication and parameter/data updates.

5.4 OPERATIONAL TESTING

- *Operational Testing of Performance:* The battery storage and PV inverter system is added onto the existing microgrid at Fort Sill. The generators are NG generators. These generators are installed on site to meet the microgrid operational requirements. For synchronization time demonstration and performance evaluation, the microgrid will be operated in a manual mode such that the generators can be started one after the other to determine the time to start. The battery inverter system is capable of operating in parallel with the generators to support the generators in both real and reactive power. The generators and the storage inverter have protection relays that will be set for over-under voltage and over-under frequency protection when the generators are starting. The PV array and the inverter are added to the microgrid at Fort Sill. The load on the PV with energy storage system can be adjusted using the variable resistive load banks. It was determined that the long duration demonstrations would be problematic given the realities of the loads available at Fort Sill. Long term tests were generally shortened from 30 to 5 days or less. The reason for the change is that the primary destination for chiller (the load) water was the Starship buildings. In the event of a base-wide utility outage, the microgrid could operate, but the Starship buildings could not. So any pumped chilled water could not be used because destination air handling equipment was unpowered. Therefore, unsupervised islanding was not allowed by base personnel. All tests needed to be performed with Eaton staff on site. However, the renewable generating sources were allowed to run continuously.

- *Timeline:* The demonstration began on March 11, 2014. The demonstration testing was completed on October 17, 2014. The five testing sessions at Fort Sill were each five business days in length.

5.5 SAMPLING PROTOCOL

- *Data Description:* Data collected includes kW, kVARs, Vs, Hz, Amperes, Seconds. The number of samples vary based upon the particular demonstration test, but are sufficient to provide full resolution of the duration of event being monitored. The Battery Management System (BMS) has an integral data logging capability. This was used to acquire data for selected short duration tests, and most long duration tests. Parameters include SOC and voltage of individual cells.

5.6 SAMPLING RESULTS

- *Post-Processing Statistical Analysis:* No significant post-processing statistical analysis is planned.

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6.0 PERFORMANCE ASSESSMENT

The following subsections provide a performance assessment of the demonstration objectives given in Section 3. Each of the 13 objectives is a subsection. A common format is used in the discussion whenever applicable. This (summary) format is:

- **Objective:** The high level description; and
- **Conclusion:** The significance of the demonstration result(s).

6.1 DEMONSTRATION 1: LOAD SUPPORT WITH RAPID GENERATOR SYNCHRONIZATION

Objective: Synchronization of both generators within 30 seconds. No loss of microgrid loads.

Conclusion: The microgrid controls with the storage inverter taking the master role and the legacy generator synchronizing to the storage inverter (SI) does allow for rapid synchronization of the generators without loss of microgrid loads. During these transients, the power quality is maintained within IEEE 1547 limits. The selection of the energy storage technology and size and the design of the storage inverter and its controls result in the desired performance.

6.2 DEMONSTRATION 2: LOAD STEP SUPPORT TO RECOVER VOLTAGE AND FREQUENCY

Objective: This demonstration shows that power optimized storage is able to support the microgrid voltage and frequency during a load step, thus reducing the time required for the voltage and frequency to stabilize.

Conclusions: This demonstration is designed to test and verify that the storage inverter along with the energy storage can perform well under load changes. The power quality performance of the microgrid during energy storage supported resistive load steps stayed within IEEE 1547 criteria for voltage and frequency. However, performing the more severe, inductive, chiller start (load step) caused 480 bus voltages to exceed IEEE 1547 limits, both low and high, over a 10 second period. The chiller starts are improved in Demonstration #11 where kVAR support improves power quality (PQ) during the start. Also, using soft starters in front of the chiller’s motor would improve the microgrid’s ability to maintain power quality.

6.3 DEMONSTRATION 3: STORAGE POWERING OF MICROGRID WITHOUT GENERATORS

Objective: Demonstrate the ability of the power optimized storage system to support the microgrid alone (without generators) maintaining power quality for a minimum of 45 seconds to a load representing 60% of the battery capacity.

Conclusion: The demonstration was designed to show that the inverter controls, battery interface, and size can support the entire microgrid. The relatively small (56kWh) energy storage is shown to support the microgrid for 45 seconds. Within 45 seconds, the generators will come online and start sharing power. This delay is also selected such that the generators are not started for short interruptions. The SI returns the microgrid to the utility, if the power outage is short. The power quality needs are also met by the SI. In some cases the test data also show the PV inverter stays connected during the transition and supports the SI for the 45 seconds. In each of these cases with about 200 kW load; the energy storage loses only 10% SOC. This proves the robustness of the design. The battery can be charging after an outage and still be immediately available for a second islanding function. The generator starting delay T2=30 seconds was selected as most interruptions in the U.S. are <30seconds.

6.4 DEMONSTRATION 4: QUANTIFY FUEL SAVINGS GIVEN PV FOR ISLANDED OPERATION

Purpose: This demonstration will quantify the fuel savings provided by high penetration PV in a microgrid where generators are primary sources when islanded.

Test Sequence/Analytical Method: Fuel consumption of the natural gas generators was calculated based on actual running data and published data from the manufacturer. PV output was projected based on actual recorded solar day data, based on a day with full sun, a cloudy day and the day with the most power fluctuations all within a 30 day period.

Test Data: The total energy generated by generator 1 and 2 are calculated for 1 month period without solar PV. The carbon dioxide (CO_2) emissions of both generators are also derived for 1 month period without solar PV. The power profiles for solar PV are measured for 1 month. The total fuel savings for natural gas generators for 1 month is calculated after adding solar PV. In addition, the total CO_2 emission reduction is also derived for 1 month after adding solar PV.

Table 2. Energy generated by solar PV for 1 month.

Day	Date	Energy in kW/hr	Day	Date	Energy in kW/hr
1	06-24-2014	346.65	16	07-09-2014	361.70
2	06-25-2014	429.75	17	07-10-2014	484.90
3	06-26-2014	338.69	18	07-11-2014	484.92
4	06-27-2014	423.54	19	07-12-2014	489.66
5	06-28-2014	295.73	20	07-13-2014	478.68
6	06-29-2014	478.76	21	07-14-2014	212.05
7	06-30-2014	491.15	22	07-15-2014	431.70
8	07-01-2014	434.42	23	07-16-2014	225.52
9	07-02-2014	302.71	24	07-17-2014	78.96
10	07-03-2014	321.84	25	07-18-2014	160.86
11	07-04-2014	418.42	26	07-19-2014	403.75
12	07-05-2014	468.77	27	07-20-2014	486.18
13	07-06-2014	487.97	28	07-21-2014	465.07
14	07-07-2014	462.65	29	07-22-2014	467.28
15	07-08-2014	374.55	30	07-23-2014	451.25
TOTAL energy generated by Solar PV in 1 month					**11,758.08 kW/hr**

Table 3. NG generators energy saving with solar PV.

Total generator energy used during 1 month period without solar PV	207,838.80 kW/hr
Total generator energy used during 1 month period with solar PV	196,077.66 kW/hr
Total energy savings during one month period	**11,761.13 kW/hr**

Table 4. NG generators fuel saving with solar PV.

Total Fuel Consumption without Solar PV during 1 month period	2,068,848 ft^3.
Total Fuel Consumption with Solar PV during 1 month period	1,961,682 ft^3
Total Fuel Saving during one month period	**107,166 ft^3**

Table 5. CO_2 emission reduction with solar PV.

Total CO_2 emission without Solar PV during 1 month period	249,406.56 Lbs.
Total CO_2 emission with Solar PV during 1 month period	235,293.19 Lbs.
Total CO_2 emission reduction during one month period	**14,113.37 Lbs.**

Conclusion: This demonstration was modified slightly to run the NG generators as little as possible. The base had limits on how many hours the generators can be run and they were to run during a power outage only.

However, as soon as the PV inverter was commissioned the PV plant was continuously run. The PV inverter was installed with an energy meter that recorded the power. The generator efficiency was used to estimate the fuel consumption as fuel consumption measurement was not available from generator or facility instrumentation. The test data on the PV was collected for long term and the test data on the generator was collected for short durations and extrapolated. The results show that the:

1. The PV will reduce the energy consumption by 5% if the Chiller were to run 24/7;
2. If the Chiller is run during the time when the sun is up (hot period), approximately 12 hours a day, energy consumption would be 10%; and
3. The assumption made was that the chiller runs at full power.

The data collected can be analyzed with different objective function to determine different condition specific results.

6.5 DEMONSTRATION 5: PV + STORAGE SUPPORT MANAGING VARIABLE LOADS

Purpose: Demonstrate the ability of microgrid compatible PV with storage support to manage variable loads while islanded, without generators online.

Conclusion: The microgrid's total PV rating is 104 kW (PV1 + PV2) and on the day of this test (March 12, 2014), the available PV was an estimated 85 kW. Therefore, 100 kW load steps applied during the test were greater than both of the load step levels required by the success criteria for this objective; 50% load step for rated PV and the 30% for the available PV. The combination of PV and energy storage maintained PQ within IEEE 1547 limits without generators. Furthermore, it should be noted at the time of the test that the battery was at less than full capacity as described previously.

6.6 DEMONSTRATION 6: PV + STORAGE SUPPORT MANAGING VARIABLE SOLAR

Purpose: Demonstrate the ability of microgrid compatible PV with storage support to manage variable solar (available power) while islanded, without generators online. Typical PV inverters go offline when the utility is not present. A PV inverter, combined with storage inverter support and microgrid controls, can power a microgrid without generators, given variable PV power and power demand within the PV available output capacity.

Success Criteria: In a solar day with the load less than 50% of average available PV, microgrid bus will remain stable, with no generators on line. Stable bus is defined as voltage maintained within +10%/-12%, and frequency within 60.3Hz/59.3Hz. The 50% level is selected based on power (and not energy) optimized battery.

Conclusion: The microgrid is able to support loads when conditions are light utilizing the renewables inverter and energy storage capabilities alone. The load could be larger than the renewables or the load can be smaller. Also, the renewables are intermittent and the energy storage inverter is shown to operate the microgrid stably. The test demonstrates the conditions where clouds intermittently cover and clear over the array. In addition, an end of the day scenario, when the PV irradiation drops, was demonstrated. The SI controls and the PV inverter controls are designed such that:

1. The SI can charge or discharge the battery to maintain a load-source balance;
2. The renewable smart inverter has a curtailment control that depends on the SOC of the battery;
3. The storage inverter is the master; and
4. The renewable inverter is not designed to operate in an island for safety purposes and so it never supports the grid on its own.

6.7 DEMONSTRATION 7: PROCUREMENT COST REDUCTION OF STORAGE

Purpose: Demonstrate that a significant equipment cost reduction can be achieved by using power optimized storage. The energy storage components in military microgrids are typically the highest cost parts of the system. Reduced cost may enable wider acceptance of microgrid in the DoD.

Success Criteria: A 67% reduction of procurement cost of storage system for the new power optimized storage versus the existing energy based storage system (flow battery) at the Fort Sill microgrid.

Data:

Table 6. Cost comparison of storage and inverter systems.

	Storage System	Inverter	Total
Energy Optimized Flow Battery Storage	$480,000	$120,000	$600,000
Power Optimized Storage with Transient Inverter	$118,000	$80,000	$198,000
Per Cent Procurement Cost Reduction	75.4	66.7	67.0

Conclusion: Table 6 above indicates that the 67% cost reduction can be achieved by virtue of using a physically smaller, power optimized battery. Along with the smaller battery come other procurement cost saving benefits such as smaller inverters, less installation infrastructure (concrete pad, mounting hardware, etc.) reduced installation costs and possibly shorter conductor lengths. The power optimized storage system cost shown above is based on production quantities. The transient rated inverter cost is an estimate based on an available Eaton production PV inverter of appropriate rating.

6.8 DEMONSTRATION 8: SMALLER FOOTPRINT FOR STORAGE

Purpose: Having a smaller equipment footprint benefits the site by allowing for more flexibility in installation location selection, including indoors, lower installation costs, and enabling simpler portability (if needed).

Success Criteria: A 50% reduction of storage system footprint for the new power optimized storage versus the existing energy based storage system (flow battery) at the Fort Sill microgrid.

Data:

Table 7. Area and volume comparison of storage systems.

	Power	kWh	Footprint	Volume
Energy Optimized Flow Battery Storage	250 kW 400 kW for 3 min	500	132 ft^2	1056 ft^3
Power Optimized Storage (Li-Ion)	400 kW	56	17 ft^2	112 ft^3

Conclusion: The power optimized storage system requires only 12.8% of the volume of the flow battery used for a previous project. The battery system (power optimized) used for this project clearly exceeds the 50% storage system footprint size reduction criteria verses the energy optimized system. This smaller physical size increases the possibility of locating the battery indoors in cases where building space is at a premium.

6.9 DEMONSTRATION 9: RAMP RATE CONTROL OF PV POWER TRANSITIONS WITH SUPPORT FROM ENERGY STORAGE

Purpose: Demonstrate the ability of the combined PV and storage to ramp the “effective” power down during a PV power reduction event (i.e., a cloud passing overhead) which can cause grid instabilities when the PV is a high penetration of local power. Storage can be used to mitigate the effect of rapid PV power reductions by having the power down ramp rather than a step.

Conclusion: PV ramp rate control was not demonstrable as PV penetration is not sufficient to have power quality impact on the utility grid at the Fort Sill location, as the grid is too “stiff.” Changes in available PV contribution are not large enough to cause out of IEEE 1547 limit disturbances. Storage will not engage transition support.

6.10 DEMONSTRATION 10: HIGH PENETRATION PV AND CONTROL OF PV POWER RAMP RATE FOR GENERATOR STABILITY

Purpose: Demonstrate the ability of the storage system to maintain a stable islanded microgrid bus during PV power steps (by ramping total power), when islanded with generators and PV sources. Solar irradiation steps can result in microgrid instabilities, given generator and high penetration PV sources (approximately 18% in this microgrid). By using storage to ramp power (up or down to the final value as needed) over a longer time, the generator output is stabilized resulting in a stable microgrid bus.

Conclusion: The data available for Demonstration #10 plus the results of Demonstrations #5 and #6 show that with energy storage, power quality of the microgrid can be generally maintained within IEEE 1547 limits in the presence of sudden load or PV power contribution changes.

6.11 DEMONSTRATION 11: MICROGRID VOLTAGE SUPPORT FROM PV INVERTER

Purpose: The PV inverter can supply kVARs to support microgrid voltage during load steps independent of the PV power available. During typical usage, the full kVA capacity of PV inverters is not utilized for delivering PV power (as solar illumination may be limited). Typically 50% of the capacity is available. This inverter capacity can be used for grid support, given integration with the microgrid control system.

Note on kVAR levels: The central PV inverter for the 86 kW solar array is rated at 250 kW, and is made up of two separate (parallel connected) 125 kW inverters. This array installation is using only one of these inverters, as the PV inverter automatically disables one inverter for less than 125 kW operations. The success criterion for Demonstration #11 states that the PV inverter will provide 125 kVAR; however, tests were run at 90 kVAR. When modifying the PV inverter controls it was discovered that a single inverter cannot produce kVAR at its rated level when the DC input is limited to 86 kW. Therefore, the tests were run at the highest kVAR level possible given the limitation.

Conclusion: Data recorded during testing indicated that the 90kVAR reactive power contribution from the PV inverter affects PQ positively when the microgrid is handling a large reactive load step, nearly bringing the starting event into IEEE1547 compliance. As stated earlier in this report, using a reduced voltage motor starter to start the chiller would allow "clean" starts whether the system was islanded or not.

Another benefit of the added reactive power support is optimizing power quality by reducing line losses. The results were that Power Factor values for the generators and the utility were at or near unity (1.00).

6.12 DEMONSTRATION 12: VALIDATE/QUANTIFY STORAGE NEEDS – PEAK POWER AND TIME DURATION

Purpose: Determine if the selected power optimized storage is of sufficient size for the Fort Sill microgrid system,;for facilitating non-disruptive islanding transitions; supporting transient load steps up; and riding through brief power quality events.

Peak power demand and pulse time have been measured in previous demonstrations. An accurate assessment of the storage need based upon the microgrid rating provides a means for determining minimized storage costs for microgrids having different ratings and characteristics.

Conclusion: The cycle life of the power optimized battery for a 50% SOC discharge (from "fully charged" roughly 80% SOC) is 15,000. For a 10% discharge, it is 170,000 cycles. Over the course of a 51 day monitoring period, 18 power quality events where recorded by the Fluke 1750. This translates to 128.9 unintentional island events annually. Given that this battery is suitably sized for peak power for the load, and maximum kWh for the islanding event, the resulting cycle life (105 years for 50% SOC discharge) is more than adequate for this application.

6.13 DEMONSTRATION 13: ASSESSMENT OF APPLICATION AREAS WITHIN DOD INFRASTRUCTURE

Purpose: Identify DoD sites that could benefit from microgrids with power optimized storage, and their potential microgrid power needs for strategic missions. This assessment will be an initial estimate of the potential DoD market for microgrids with power optimized storage. These would be facilities with significant existing on site generation and/or renewables.

Data: A series of applicable technology transfer targets were identified and include DoD installations with existing and planned microgrid operations. Prime technology transfer targets are sites that have been identified based on a combination of high energy costs, energy security challenges, and planned/proposed microgrid initiatives.

The following is a detailed description of the prime candidate sites for the demonstrated technology. These will have the greatest benefit/impact having microgrids with the proposed technology.

Miramar Marine Corps Air Station (MCAS), CA: A new microgrid is being planned at Miramar MCAS for implementation in fiscal year 16 timeframe. This will be one of DoD's largest microgrid investments on the order of $15M. This will be an energy security microgrid to incorporate renewables including landfill and PV resources.

Joint Base Pearl Harbor Hickam, HI (JBPHH): Distributed inverter technology can be implemented in an existing circuit level SPIDERS microgrid at JBPHH that incorporates 2 megawatts (MW) of diesel generation, 150 kw of PV, and a waste water treatment plant with 1 MW of load. The SPIDERS microgrid is configured to accept additional infrastructure improvement including energy storage and distributed inverter technology. Energy cost greater than $.25/kWh.

Pacific Missile Range Facility, Kauai, HI (PMRF): PMRF has significant energy security and quality challenges at a single circuit from Kauai Island Utility Cooperative, which serves the base at the end of the feeder with no redundancy. As a consequence, the installation routinely transitions to installation back up power during missile testing and other energy intensive activities. Near-by renewable energy includes methane based landfill gas and PV. Energy cost greater than $.45/kWh.

Finneyagin Marine Corps Base (MCB), Guam: This is a MCB in Guam that is being planned and designed by Naval Facilities Engineering Command (NAVFAC). It will support a number of critical operational missions for both Navy and Marine Corps in the Pacific. Load estimated at 4-6 MW. Energy cost greater than $.35/kWh.

Twentynine Palms MCB, CA: An ESTCP-funded activity to incorporate microgrid technology across PV, chilled water, energy storage, chilled water, CoGen, and fuel cell technology over the installation electrical distributions system. Distributed inverter technology can be installed to interconnect the energy storage or PV to the microgrid.

U.S. Army Fort Sill Lawton, OK: Eaton proposed repurposing the microgrid of this project and expanding to a total of 1.8MW. The expansion of the microgrid includes integration of legacy generators in the waste water treatment plant to the microgrid in building 5900, and would include the load presented starship (dormitory) 6007. The microgrid will be able to handle the increased load with the addition of low cost Absorbent Glass Mat type energy storage.

7.0 COST ASSESSMENT

The microgrid technologies to be demonstrated in this project hold enormous promise to the DoD. Successful implementation of this technology will provide hard data that:

- Power storage systems provide the lowest cost power surety/reliability microgrid solution; and
- Microgrid enabled renewables (using the microgrid compatible inverter) provide an energy efficient alternative to existing microgrid approaches, where fuel based sources are the mainstay.

Some of the specific and measurable benefits to the military include: improved energy security through reduced down time for critical loads; 67% reduction in acquisition costs for required microgrid storage systems; ability to integrate legacy generators into microgrids; reduction in overall energy consumption; offset energy demand from the grid; on-site renewable energy generation; lower energy cost; reduced disposal or recycling costs; and decreased carbon emissions.

The system is capable of accepting different types of renewable energy sources, thus the renewable energy source used can be determined and sourced based on geographical location. Because this technology is not geographically limited, it can easily be employed at any DoD or civilian facility worldwide.

Reduction in Energy Storage System Cost

Energy Optimized Storage System: Eaton is currently completing a microgrid demonstration at Fort Sill (for a Construction Engineering Research Laboratory [CERL] sponsored project). The demonstration is a 400 kW microgrid with solar, wind, NG generation, and an energy storage system based upon a 500 kVA continuously rated inverter, as well as a ZBB flow battery system rated for 250 kW for 2 hours (and 400 kW for 3 minutes). This system can power 250 kW of the islanded microgrid for 2 hours, supporting microgrid load during a long term islanding situation with a low emissions source. As shown in Table 8, the cost for this traditional energy optimized storage and inverter solution is $600,000. (Note: The energy storage at Fort Sill was actually leased for this demonstration and not purchased due to the high capital costs and development nature of the project).

Table 8. Cost comparison of storage and inverter systems.

	Storage System	Inverter	Total
Energy Optimized Flow Battery Storage	$480,000	$120,000	$600,000
Power Optimized Storage with Transient Inverter	$118,000	$80,000	$198,000

The traditional energy storage currently used at Fort Sill can be replaced by a power storage inverter, which is a 250 kW continuously rated unit, modified to have a transient 400 kW 1 minute rating. The storage (Li-ion battery based) is sized for providing 400 kW for 1 minute. This storage system will allow for ride through during loss of the utility. It will also enable the PV system to power the islanded microgrid during short term clouds passing over the PV system or load steps without starting the generator units. As shown in Table 8, the cost for the power optimized storage with transient inverter is $198,000 (or 33% the cost of traditional energy optimized storage).

The data provided in Table 8 can be extrapolated linearly as well. In other words, the cost of energy optimized flow battery storage for a 6-8MW microgrid will be $9-12M, and the cost of power optimized storage will be $3-4M.

Battery Lifetime

Based upon available vendor data, the nLTO battery lifetime will be at least as long (5 years) as that of the flow battery cells.

- Flow Battery: The manufacturers (ZBB) table states that Zinc-Bromide flow batteries have a stack (cell) life of 5-6 years, after which they require replacement.
- nLTO Battery: For Eaton specified power cycling application needs, the vendor has indicated at least 5 years life for the maximum duty condition, and greater than 5 years for nominal duty conditions.

Also per the vendor:

- Altairnano has completed tests involving over 16,000 cycles of continuous charging and discharging of the battery cells and found minimal degradation to the product. The cells still retained over 80% of their original charge capacity at the end of these tests. This cycle life is an order of magnitude greater than any other Li Ion battery technology, making Altairnano’s nLTO technology the best technology suited for long life applications.
- The degradation of Altairnano batteries due to calendar life is also much better than other lithium technologies, losing less than 1% of their energy capacity after 25 years, making it less likely that the batteries will ever need to be replaced.

Residual Value Calculation: The project team assumed a total expected life of the system to be 24 years. The inverter portion of the system was straight line depreciated over that 24 year period such that the residual value at 24 years is $0. There is an 8 year life on the energy storage portion of both systems. Assuming two system overhauls (at 8 and 16 years), the book value of the initial energy storage components and capital replacement costs were straight line depreciated over individual 8 year periods, again so that the residual value at 24 years is $0.

Operations, Maintenance, and Repair (OM&R) Calculations: This model assumed a minimal amount of ongoing OM&R costs annually.

Capital Replacement Calculations: This model assumes both systems have 70% of their cells or modules that need to be replaced every 8 years. Additionally, the model assumes some reduction in acquisition costs of battery technology over time to make this replacement cost more affordable. The project team assumed a 50% cost reduction (from present) for the first lithium battery replacement ($82,600 current replacement will be $41,300 in 8 years). A 20% cost reduction was further assumed for the second lithium battery replacement ($33,040 in 16 years). For flow battery technology, the project team did not anticipate such a learning curve and volume increase to drive down costs. A 30% cost reduction was assumed (from present) for the first flow battery replacement ($336,000 current replacement will be $235,200 in 8 years)and a total 50% cost reduction from present was assumed for the second flow battery replacement ($168,000 in 16 years).

7.1 COST MODEL

This model addresses the costs related to the demonstration of the technology (power optimized battery, storage inverter, solar PV and associated controls). Costs related to installation and verification of the Fort Sill microgrid for CERL is not considered.

Table 9. Microgrid modified for power optimized energy storage.

Cost Element	Data Tracked During the Demonstration	Estimated Costs
Hardware capital costs	Power optimized battery, storage inverter, solar PV system, and associated controls	$418,755.17
Installation costs	Eaton Electrical System & Services - labor and materials, including design	$672,436.01
Consumables	NG (Generators 1 & 2) only consumed when islanded	Oklahoma NG Industrial Price: 10.11 USD/thou cf for Aug 2014
Facility operational costs		Unknown
Maintenance	• Monthly generator exercise and battery maintenance charge • 2 hours monthly	Fort Sill DPW hourly labor cost is not known.
Hardware lifetime	Estimated component lifetime is examined previously in this section.	
Operator training	Estimate of training costs (4 hours training session)	Trainer travel and labor: $1500.00 Trainee(s): Fort Sill DPW hourly labor cost is not known.

DPW = Department of Public Works

- *Power Optimized Battery:* The 400 kW battery higher volume cost is estimated at $118,000 or $295 per kW. When a battery size is determined for a new system, employing the technology the "per kW" cost can be used to estimate the battery cost. As this battery technology matures the per kW cost are expected to decrease.
- *Microgrid Capable Storage Inverter:* The inverter used in this demonstration was rated at 500 kW and a custom assembly for the CERL Fort Sill microgrid project; it had a cost estimated at $120,000. For future uses of the technology, microgrid storage inverters specifically tailored to power optimized battery applications would be used. In the case

of this microgrid, an appropriately rated storage inverter is estimated to have a cost of $80,000. In future systems, the inverter capacity will need to be determined in accordance with the battery rating requirements.

- *Solar PV Commercial Size Array:* The technology demonstrated was designed to include significant support from PV. The PV industry rule-of-thumb for installed cost per watts of a commercial size PV system is $4.60. For the 86 kW array of this demonstration, $4.60/Watt translates to $396,000. As with the other system components described above, array size will need to be determined to serve the purposes of the application.
- *Microgrid Controls for Legacy Generators:* Controls must be designed and programmed such that the technology can work in cooperation with the balance of microgrid components. Code design and programming of the Programmable Logic Controllers (PLCs) used in the system had a cost of $29,010. CAT-ISO controller programming costs were $32,000.

7.2 COST DRIVERS

The power optimized battery technology is an inherently less costly energy storage method than the typical energy optimized batteries frequently used in microgrid installations. A comparison of the main cost drivers of these two technologies are described in Section 6, Demonstrations #7 and #8. Power optimization reduces the rating and physical size of energy storage, lowering procurement, inverter, and installation costs. The cost driver is therefore the cost of the lithium-titanate battery technology, which is expected to decrease as it matures and comes into greater levels of production.

7.3 COST ANALYSIS AND COMPARISON

Table 10 below provides a budgetary estimate for expanding the existing Fort Sill microgrid using NG generators with a power battery and microgrid controls to manage renewable and other generating sources. This expansion of the microgrid includes integration of legacy generators in the waste water treatment plant to the microgrid in building 5900, and would encompass a total power of approximately 2 MW. The implementation of this over a mile-long 13.2 kV line will be a new milestone for microgrid technology at Fort Sill.

Scope and Cost

1. Install a pole-mounted re-closer to island the starship 6007, building 5900, and the waste water treatment plant.
2. Modify chiller control to enable (reduced voltage) starting with the microgrid.
3. Add low cost storage to support larger distributed load.
4. Add load shedding and communications across the buildings.

Table 10. Task cost estimate.

Description of Task		Cost Estimate
1	Electrical and control system design	$35,000
2	New hardware to be added	$290,000
3	Update microgrid and waste water treatment plant generator controls	$175,000
4	Installation and wiring of the new hardware	$250,000
5	Integration, testing, and commissioning	$255,000
6	Demonstration and training	$35,000
7	Program management	$70,000
	Total Budgetary Estimate	**$1,110,000**

This expansion would enable a higher power capacity microgrid offering extended islanded operation with critical loads included. As lower cost power optimized storage is applied, the overall costs become dominated by site construction costs typical of any electrical expansion or refurbishment, and independent of storage technology employed.

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8.0 IMPLEMENTATION ISSUES

The following are microgrid site implementation issues and technology lessons learned that should be addressed early in future similar projects, or will benefit the future implementation of the demonstrated technology.

8.1 REDUCED VOLTAGE STARTING (CHILLER)

Starting the chiller, even the smaller chiller #3 unit, is an abrupt reactive load step that taxes the utility grid briefly as well as causing mechanical stresses on all connected equipment. For the microgrid, chiller starts cause voltage and frequency fluctuations that constitute power quality events.

Lesson Learned: It is Eaton's recommendation that for large inductive loads such as large motors and chillers, reduced voltage starting techniques be used where possible.

8.2 END USER CONCERNS

Eaton completed the on-site activities for the demonstration at Fort Sill. One of the final tasks was to provide microgrid system operator training to Fort Sill DPW and other staff that might be involved with periodic maintenance of the microgrid. It became clear over the course of the training that no individual or department had clear responsibility for ownership and maintenance of the system.

Lesson Learned: Eaton's recommendation is that the responsible owner and future operator be identified early in the deployment process so that the individual or group "owner" is familiar with the microgrid as the installation unfolds to acquire a fuller understanding of the technology, its intended use, and future maintenance issues.

8.3 SITE LOAD AVAILABILITY

Chiller #3 served as the primary microgrid load, but other heating, ventilation, and air-conditioning (HVAC) equipment (cooling tower, air handling equipment for HVAC in Starship buildings, etc.) that are required to make the chiller operations useful were not included as part of the load. Having the microgrid drive these additional loads, to control a full system, would have enabled a more effective demonstration, and also would have allowed Eaton to perform the longer term (months of continuous operation) demonstration tests that had been planned as part of the original objectives. It is highly recommended that the Fort Sill microgrid be expanded to include all loads on a full MV feeder on the east side of the post. This would enable extended operation in islanded mode with a full spectrum of sources and loads within the autonomous island.

8.4 LESSON LEARNED – MULTIPLE PACKS OF PARALLEL BATTERIES

The BMS calculation of SOC is based on the SOC of all the racks. If the SOC of one rack is low, it affects the SOC of the entire system. Isolating a bad rack is more efficient than keeping it in the microgrid with its partial capacity.

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9.0 REFERENCES

1. Olson, Gary. *Paralleling Dissimilar Generators: Part 1 – An Overview*. Power topic #9015. Technical information from Cummins Power Generation; White Paper.

2. IEEE Standard 1547. Standard for Interconnecting Distributed Resources with Electric Power Systems was approved by the IEEE Standards Board in June 2003. It was approved as an American National Standard in October 2003. 1547a (Amendment 1) was published in 2014.

3. "Design of the Fort Sill Microgrid," A. Paquette, V. Bhavaraju, S. Krstic, P. Theisen, R. Harley, 2014 IEEE Energy Conversion Congress & Expo.

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APPENDIX A

POINTS OF CONTACT

Point of Contact	Organization	Phone Fax E-Mail	Role In Project
Dr. Vijay Bhavaraju	Eaton Corp – Research & Technology	Phone: (414) 449-6871 E-Mail: VijayBhavaraju@Eaton.com	Technical Team
B. Thomas (Tom) Pier	Eaton Corp – Research & Technology	Phone: (414) 449-6565 E-Mail: btompier@eaton.com	Technical Team
Lucinda Shane	Eaton Corp – Research & Technology	Phone: (414) 449-6607 E-Mail: lucindakshane@eaton.com	Manager, Government Contracts
Andrew Teague	U.S. Army, Fort Sill	E-Mail: andrew.d.teague.ctr@mail.mil	DPW, Energy Manager

ESTCP

ESTCP Office
4800 Mark Center Drive
Suite 17D08
Alexandria, VA 22350-3605
(571) 372-6565 (Phone)
E-mail: estcp@estcp.org
www.serdp-estcp.org