EXECUTIVE SUMMARY

Advanced Phasor-based Control of Energy Storage Micro-grids

ESTCP Project EW19-5163

DECEMBER 2019

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ACRONYMS AND ABBREVIATIONS

ACT	Active Control Technology
AFB	Air Force Base
ARB	Air Reserve Base
CASIO	California Independent System Operators
CES	Customized Energy Solutions
C-HIL	Controller Hardware-in-the-Loop
CoMETS	Competitive Market Evaluation Tool for Storage
DCM	Demand Charge Management
DER	Distributed Energy Resources
DR	Demand Response
ESS	Energy Storage System
ESTCP	Environmental Security Technology Certification Program
kW	Kilowatt
kWh	Kilowatt Hour
LFP	Lithium Iron Phosphate
Li-ion:	Lithium Ion
LoG-RT	Loss of Grid Ride-Through
MTBF	Mean Time Between Failures
NAS	Naval Air Station
NB	Naval Base
NMC	Lithium Nickel Manganese Cobalt Oxide
Pax	Patuxent
SoC	State-of-Change
UPS	Uninterruptible Power Supplies

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Raytheon Integrated Defense Systems contributors were David Altman and Benjamin Robistow.

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1.0 INTRODUCTION

Environmental Security Technology Certification Program (ESTCP) project EW19-5163 studied the use of Lithium Ion (Li-ion) Energy Storage Systems (ESS) coupled with advanced phasor-based microgrid control technology to improve the economics, reliability, and performance of DoD installation microgrids.

Two Li-ion chemistries were considered: Lithium Nickel Manganese Cobalt Oxide (NMC), typically supplied by Samsung SDI or LG Chem, and Lithium Iron Phosphate (LFP), typically supplied by Powin or BYD. Either battery type would be employed as part of a DynaPower ESS, with sizes ranging from 100kW to over 3000kW and durations ranging from 1-6hrs of total storage.

These batteries, as well as other components in the microgrid, are controlled by PXiSE's Active Control Technology (ACT) phasor-based microgrid controls. PXiSE's ACT combines high speed synchrophasor-based measurements, closed loop feedback control with real / reactive power decoupling, and cost function-based system operation optimization.

A combination of techno-economic and reliability analysis was performed for conceptual energy storage-enhanced microgrids at five different DoD installations. Techno-economic analysis was performed to optimize net life cycle costs associated with deployment and operation of the energy storage-enhanced microgrid. Reliability analyses were performed for each installation to determine critical load coverage probability for islanding through outages up to 168hrs with varying storage sizes, durations, number of ESS units, ESS mean time between failures (MTBF), and numbers of removed diesel generators.

One of the underlying assumptions of the reliability analysis is that all available renewable energy in any hour can be used, provided it does not exceed system kilowatt hour (kWh) capacity. This is not typically a valid assumption in diesel generation-based microgrids, but can be for grid-forming inverter-based microgrids. However, unlike networked diesels, grid-forming inverters represent a single point of failure and can reduce reliability. To address this potential shortcoming, the EW19-5163 microgrid concepts use PXiSE's ACT controls to enable energy storage to be divided into multiple units with the capability to back each other up in the event of ESS failure.

Similarly, one of the underlying assumptions of the techno-economic analysis was that the energy storage can be used for any grid-tied use case in any hour, and that some use cases can be performed in the same hour. To realize this assumption, the EW19-5163 microgrid concepts use PXiSE's ACT to control energy storage and other Distributed Energy Resources (DER) to manage power and energy flows at appropriate points in the microgrid to simultaneously satisfy the criteria associated with each grid-tied use case.

To evaluate the efficacy of the PXiSE ACT controls in providing the aforementioned capabilities, Controller Hardware-in-the-Loop (C-HIL) testing was performed using a modified version of the C-HIL facility and models being used on ESTCP project EW-201606. Tests were performed using a test plan developed through a collaboration between Raytheon and MIT-Lincoln Labs to address IEEE 2030.8 Microgrid Controller Testing standard requirements.

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2.0 OBJECTIVES

There were three overarching objectives of EW19-5163 defined to address reliability, economics, and technical feasibility of using advanced phasor control and Li-ion energy storage in a DoD installation microgrid. The comparative baseline was defined by ESTCP as a microgrid employing a set of networked diesel generators. Baseline microgrids for each installation are depicted in Figures 3-7 in the body of the full report. The three overarching objectives are:

1. Quantify improved reliability performance relative to a baseline diesel microgrid analysis.
2. Define an economic operational concept that supports cost-effective implementation.
3. Test PXiSE ACT microgrid controls to validate functions that enable 1) and 2).

These overarching objectives served as the basis of eight performance objectives that were addressed via reliability and techno-economic analysis of energy storage microgrid concepts at five DoD installations, and C-HIL testing of PXiSE ACT controls.

2.1 RELIABILITY PERFORMANCE OBJECTIVES

1. Provide operation with reliability ≥ the all-diesel baseline microgrid to meet 100% of installation critical and ride-thru load.
2. Provide operation with reliability ≥ the all-diesel baseline microgrid at 100% installation critical and ride-thru load to meet 130% of installation critical and ride-thru load.
3. Provide operation with reliability ≥ the all-diesel baseline microgrid at 100% installation critical and ride thru load to meet 10% and 30% of installation critical and ride-through load when no diesel fuel is available.

2.2 TECHNO-ECONOMIC PERFORMANCE OBJECTIVES

1. Reduce net life-cycle costs of deployment and operation (corresponding to technical objective 1 above) relative to the all-diesel baseline microgrid.

2.3 CONTROLLER HARDWARE-IN-THE-LOOP TESTING OBJECTIVES

1. Demonstrate transitions and stable islanded operation using an “under-sized” grid-forming ESS, complemented by an ESS receiving high-speed real / reactive power commands.
2. Quantify the ability to reduce fuel utilization and ESS throughput / cycling through high speed control.
3. Illustrate the ability to ride-thru failure of a grid-forming ESS during islanding using a redundant ESS with Loss of Grid Ride-Through (LoG-RT) capability.
4. Quantify the ability to provide improved microgrid demand management capability at the Point of Interconnect through more effective utilization of available DERs.

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3.0 ENERGY STORAGE TECHNOLOGY(IES) AND DOD INSTALLATIONS SELECTED FOR MODELING

EW19-5163 considered Li-ion batteries as part of an integrated ESS. Li-ion batteries were chosen due to their low cost, acceptable cycle life, and versatility to support various grid-tied use cases to produce economic benefits. Their low capital cost (<$400/kWh) enables short-duration Li-ion storage systems to be cost competitive with both comparably sized diesel generators and Uninterruptible Power Supplies (UPS), including the inverter and balance of plant hardware.

Li-ion batteries were used within a DynaPower ESS that included an inverter capable of grid-forming and dynamic transfer to support LoG-RT. As demonstrated in prior projects, (e.g., EW-201242), grid-forming inverters are a proven solution to incorporate renewables within a microgrid, improving reliability and reducing fuel consumption. As is being demonstrated on EW-201606, DynaPower's dynamic transfer technology enables LoG-RT to seamlessly accommodate unplanned outages. When combined with appropriate switching, this can enable elimination of dedicated UPS units in favor of more cost effective multi-function ESS units.

To optimally control the ESS and other DERs, the microgrid designs considered in this study use PXiSE's ACT microgrid controls. PXiSE's ACT provides high speed control capability to exploit the dynamic response characteristics of the ESS and allow decoupled control of real and reactive power. Specifically, PXiSE's control improves reliability by allowing the use of multiple grid-forming ESS units that are undersized, in lieu of one larger unit. It also improves economics by allowing precise control of power at multiple points in the microgrid to simultaneously satisfy multiple value-stacking objectives.

Five different installations were investigated for the project:

1. Fort Bliss—New Mexico / Texas
2. Holloman Air Force Base (AFB)—New Mexico
3. March Air Reserve Base (ARB)—California
4. Naval Air Station (NAS) Patuxent (Pax) River—Maryland
5. Naval Base (NB) Ventura County—California

Fort Bliss was specified by ESTCP; the other four installations were selected based on their local market characteristics and/or tariff information at the time of the project proposal.

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4.0 MODELING METHODOLOGY

Two types of modeling were pursued in this project. Techno-economic analysis was performed to determine the economically optimal size and duration of the energy storage by considering various combinations of grid-tied use cases. Reliability analysis was conducted to determine critical load coverage probability vs. islanding duration.

The optimized size of the energy storage from the economic analysis determined the number of UPS units that could be eliminated. The reliability analysis determined the number of diesel generators that could be eliminated. UPS and diesel generator reductions were incorporated into the techno-economic analysis to arrive at the final cost results.

4.1 TECHNO-ECONOMIC ANALYSIS

Techno-economic analysis was done by Customized Energy Solutions (CES) using their Competitive Market Evaluation Tool for Storage (CoMETS) tool. The analysis considered a variety of behind and in front of the meter use cases which varied with location. Storage size and duration were optimized for the most economically favorable use case(s) for each installation.

4.2 RELIABILITY ANALYSIS

Reliability analysis was conducted by Raytheon using a custom model based on an National Renewable Energy Laboratory-developed, ESTCP provided, probabilistic methodology to determine critical load coverage probability vs. islanding duration. An energy storage dispatch strategy was implemented within the model that sought to use energy storage to minimize the number of generators required to meet the critical load for each islanding duration. Numerous cases were run to vary ESS size, duration, quantity of units comprising the total storage, and MTBF.

4.3 CONTROLLER HARDWARE-IN-THE-LOOP

C-HIL testing was performed to evaluate the performance of the PXiSE ACT controls by modifying a model of the Otis Air National Guard Base Microgrid developed under EW-201606[1]. This entailed dividing the ESS model used on EW-201606 into two half-size units and providing a PXiSE ACT controller access to simulated relay phasor data and DER control interfaces. Testing was performed for four groups of tests that represented a subset of the IEEE 2030.8 testing performed on EW-201606 using the baseline Raytheon-developed control solution. These tests were chosen specifically to enable testing of the aforementioned performance objectives 5-8.

[1] The EW-201606 C-HIL model / hardware was used to cost effectively test ACT functionality with existing DERs.

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5.0 PERFORMANCE ASSESSMENT

Performance assessment comprised two parts: 1) reliability analysis for the proposed storage-enhanced microgrid configurations at each of the five installations, and 2) C-HIL testing evaluating the ability of the PXiSE ACT controls to provide the aforementioned capabilities required to realize the assumptions made in the reliability and techno-economic analysis.

5.1 RELIABILITY ASSESSMENT

Table 1 summarizes the reliability analysis performance assessment results. As noted previously, the storage size and duration were the result of the techno-economic optimization, and the numbers of generators removed were the maximum possible while meeting the 100% Critical Load Reliability requirement. None of the configurations provided appreciable coverage at 130% Critical Load—this is not surprising since the number of generators was minimized for the 100% critical load profile. Most configurations provided >24hrs coverage for 10% and 30% Critical Load Reliability (without generators). Fort Bliss was the exception, due to high critical load and relatively small storage size driven by relatively poor grid-tied economics. NB Ventura achieved 3hrs at the 30% critical load requirement; however, the periods where the load coverage probability fell below the requirement were marginal, limited by storage MTBF. A follow-up analysis showed that by increasing MTBF, >24hrs of coverage would be achieved with the same storage size.

Table 1. Summary of Reliability Results

	Fort Bliss	Holloman AFB	March ARB	NAS Pax River	NB Ventura
Storage Size	1700kW	2400kW	2400kW	29400kW	2500kW
Storage Duration	1hr	2hr	1hr	1hr	1hr
# Diesel Generators	7 (1 removed)	7 (2 removed)	3 (1 removed)	10 (2 removed)	9 (1 removed)
# UPS	4 (none removed)	4 (9 removed)	0 (all removed)	0 (all removed)	0 (all removed)
100% Critical Load Reliability	>168hrs above requirement	>168hrs above requirement	>168hrs above requirement	>168hrs above requirement	>168hrs above requirement
130% Critical Load Reliability	<1hr above requirement	<1hr above requirement	4hrs above requirement	3hrs above requirement	<1hr above requirement
10% Critical Load Reliability*	>24hrs above requirement	>24hrs above requirement	>24hrs above requirement	>24hrs above requirement	>24hrs above requirement
30% Critical Load Reliability*	<1hr above requirement	>24hrs above requirement	>24hrs above requirement	>24hrs above requirement	3hrs above requirement

* No diesel generators

Although in a few instances it may have been possible to reduce the number of required generators further with increased storage size or duration, in general eliminating more than two generators was economically problematic.

UPS units, on the other hand, were easy to eliminate, provided the design could be implemented in a way that would provide equivalent functionality to the existing UPS. To achieve this, our results assume that storage is implemented using multiple modular ESS units that can be co-located with critical load requiring ride-thru. This is possible because of the grid-forming capabilities of our ESS approach, and control capabilities of PXiSE ACT microgrid controls.

5.2 CONTROLLER HARDWARE-IN-THE-LOOP ASSESSMENT

C-HIL testing to address performance objectives 5-8 was performed in four test groups mapped into the IEEE 2030.8 standard using the test plan that was developed for EW-201606.

Test Group 1 included nine tests addressing transitions to and from islanding. In general, to pass the test, any microgrid controller, and, in particular, the PXiSE ACT controller would need to execute the scenario without tripping protective relays that would result in a partial or complete failure of the microgrid. Planned islanding tests were performed under heavy import and heavy export conditions. Un-planned islanding tests were also performed for heavy import and export; each un-planned islanding event was divided into 3 sub-tests for each condition (auto-reconnect nominal state-of-change (SoC) loss-of-grid ride-thru, loss-of-grid ride-thru with low or high ESS SoC). PXiSE ACT controls successfully completed all of these tests. The re-connection test was also completed successfully by the PXISE ACT control without incident. Notably, the PXiSE ACT controls were able maintain wind turbine production during all transitions, which represents an improvement over the baseline where shutting down and re-starting was required to avoid tripping the turbine.

Test Group 2 included 5 tests addressing steady-state islanding performance. The tests evaluated the ability of the PXiSE ACT controls to react to variations in DER outputs, and to optimize DER dispatch strategies to maximize microgrid efficiency and reliability. Success was achieved by not tripping protective relays that would cause the microgrid to partially or totally fail, and increasing islanding efficiency and reliability relative to the base case from EW-201606. DER variation tests included varying ESS output frequency and voltage, wind turbine power output (kW) and generator power output (kW). All of these tests were completed successfully. Notably, the independent reactive power control capability enabled by the PXiSE controller enabled faster ramping of the diesel generator, avoiding a reverse kVAR fault observed in the baseline. Steady state islanding efficiency and reliability testing was completed.

Test group 3 included two tests evaluating the ability of the PXiSE ACT controls to support "redundant ride-thru" by using the non-grid-forming ESS to take over grid-forming responsibilities in the event the grid-forming ESS fails. Success was defined as maintaining load coverage during and following the failure of the primary grid-forming ESS while charging or discharging. Both tests were successful demonstrating that multiple grid-forming ESS units can back each other up in a microgrid similar to the way a networked set of diesel generators works.

Test group 4 included one test to evaluate the ability of the PXiSE ACT controls to manage power flow within the microgrid during grid-tied operation using multiple DERs to meet a particular power control objective. This test represents a scenario where demand management is a continuous need and may be complicated by variable renewable generator performance and potentially conflict with other ongoing economic use cases (e.g., frequency regulation). This test was again completed successfully by the PXiSE ACT controls, demonstrating the ability of the PXiSE ACT controls to manage power flow using multiple ESS units and other DERs.

6.0 COST ASSESSMENT

Table 2 summarizes results from techno-economic optimization for current pricing data. Most notably, columns E and J show the annualized net cost per kW protected critical load for both the baseline and storage-enhanced microgrids. Column E is the summation of columns A-D and column J is the summation of columns A-D and F-I. In general, market participation provided the greatest benefits, followed by UPS elimination, and then diesel generator elimination. NAS Pax River achieved the best results, realizing a profitable microgrid by value stacking frequency regulation, demand response (DR), and demand charge management (DCM). Holloman AFB showed the second-best results through DR, DCM, and retail arbitrage. March ARB and NB Ventura produced comparable results, combining DCM, DR, retail arbitrage, and spinning reserve. We note that better economics could have been achieved by performing frequency regulation in California Independent System Operators (CAISO); however, CAISO rules would require the storage to be connected in front of the meter in a way that would very limiting and likely be impractical for a DoD installation microgrid. Fort Bliss showed the least favorable results. This was primarily the result of the limited market participation options available (DCM and retail arbitrage), and the high base load of the facility combined with the tariff resulting in small addressable demand charges. A small benefit was obtained through these functions and elimination of a diesel generator.

Table 2. Summary of Cost Results

	Peak Critical Load (kW)	Diesel Gensets (A)	UPS (B)	Microgrid (C)	DR & Peak Shaving Savings (D)	Annual Net Cost of Protecting each KW of Peak Critical Load (E)	Energy Storage (F)	DCM & Wholesale Revenues (G)	Diesel Genset Considered Obsolete because of Storage (H)	UPS Considered Obsolete because of Storage (I)	Annual Net Cost of Protecting each KW of Peak Critical Load with Storage (J)	ES Size (kW)	ES Duration (hr)
Holloman AFB	5996	$49	$22	$36	($10)	$98	$35	($51)	($11)	($16)	$55	2400	2.7
March ARB	600	$121	$52	$243	$0	$416	$192	($240)	($30)	($52)	$286	2400	1.3
NAS Patuxent River	8014	$49	$22	$36	($10)	$98	$176	($330)	($8)	($22)	($86)	29400	1.3
NAS Patuxent River	8014	$49	$22	$36	($10)	$98	$23	($64)	($8)	($16)	$33	3000	1.3
Naval Base Ventura County	4003	$57	$23	$54	$0	$135	$30	($42)	($8)	($23)	$91	2500	1.3
Fort Bliss	12507	$47	$18	$18	$0	$83	$7	($5)	($6)	$0	$78	1700	1.3

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7.0 STUDY CONCLUSIONS AND OUTCOMES

In summary, our Phase I study concludes that state of the art short-duration Li-ion energy storage can be used in a DoD installation microgrid to improve reliability with significantly reduced cost vs. an all-diesel microgrid. The techno-economic analysis showed that value stacking market participation functions is most important, followed by UPS elimination. Reliability analysis showed that 1-2 diesel generators can be cost effectively eliminated if appropriately storage is included in the design. C-HIL testing showed that PXiSE's ACT controls can enable multiple "undersized" ESS units realize an inverter grid-forming microgrid. This outcome validates key assumptions in the techno-economic and reliability analyses regarding renewable integration, multi-ESS microgrid reliability, and value stacking. These results motivate follow-on work to demonstrate a Li-ion ESS and ACT phasor control-based microgrid.