Test Report: Raytheon / KTech RK30 Energy Storage System

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⊞ Sandia National Laboratories

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Abstract

The Department of Energy Office of Electricity (DOE/OE), Sandia National Laboratories (SNL) and the Base Camp Integration Lab (BCIL) partnered together to incorporate an energy storage system into a microgrid configured Forward Operating Base to reduce the fossil fuel consumption and to ultimately save lives. Energy storage vendors will be sending their systems to SNL Energy Storage Test Pad (ESTP) for functional testing and then to the BCIL for performance evaluation. The technologies that will be tested are electro-chemical energy storage systems comprising of lead acid, lithium-ion or zinc-bromide. Raytheon/KTech has developed an energy storage system that utilizes zinc-bromide flow batteries to save fuel on a military microgrid. This report contains the testing results and some limited analysis of performance of the Raytheon/KTech Zinc-Bromide Energy Storage System.

ACKNOWLEDGMENTS

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NOMENCLATURE

%OS	Percent Overshoot
BCIL	Base Camp Integration Laboratory
COTS	Commercial off the Shelf
DETL	Distributed Energy Technology Lab
DOE	Department of Energy
ESS	Energy Storage System
ESTP	Energy Storage Test Pad
FOB	Forward Operating Base
SOC	State of Charge
SNL	Sandia National Laboratories

1. INTRODUCTION

The Department of Energy Office of Electricity (DOE/OE), Sandia National Laboratories (SNL) and the Base Camp Integration Lab (BCIL) partnered together to incorporate an energy storage system into a microgrid configured Forward Operating Base to reduce fossil fuel consumption and to ultimately decrease the use of military convoys. Energy storage vendors made available their systems to the SNL Energy Storage Test Pad (ESTP) for functional testing and then to the BCIL for performance evaluation. The technologies that will be tested are electro-chemical energy storage systems comprising of lead acid, lithium-ion or zinc-bromide. Testing at Sandia National Labs includes a capacity test, Commanded Response test, frequency response test, voltage response test, and inverter characterization test. Through these tests, Sandia will analyze the performance and design and provide recommendations for each Vendor. Raytheon / KTech provided Sandia their RK30 Energy Storage System for testing (the results are documented in this report).

2. TECHNOLOGY DESCRIPTION

The Raytheon / KTech RK30 Energy Storage System uses twelve RedFlow Zinc-Bromide Battery Modules (ZBMs) and six single phase inverters to sink, store, and supply electrical energy. Each ZBM is rated to hold up to 10kWh and each inverter is rated at 5kW making the system rated at 30kW and 120kWh. The inverters are 208VAC phase to phase inverters and are connected to a delta to wye isolation transformer to allow an electrical wye system interface.

Figure 1 Raytheon/KTech energy storage system delivered to Sandia

Zinc-bromide flow batteries electroplate zinc onto the anode to convert electrical energy to chemical energy. Reversing this reaction releases the stored energy. Zinc-Bromide batteries such as the ZBM have several unique characteristics that set them apart from other battery chemistries.

- Zinc-Bromide is a normally empty system; it is fully discharged during storage and shipment and hence has zero DC voltage on its terminals.
- Other battery chemistries can be discharged to zero volts however doing so can be inefficient and degrade life as is the case with lead-acid or become more volatile as is the case with Lithium-Ion.
- Charging it puts voltage on the DC bus, which it will hold until discharged again.
- Just as lead-acid batteries need to be fully charged on a regular basis to maintain life, zinc-bromide batteries must be fully discharged every few days to maintain life.
- Fully discharging the battery is necessary in order to mitigate zinc dendrites that can puncture the separator when allowed to grow.
- This full discharge conditioning cycle is called stripping as it strips all plaited zinc from the battery leaving clean, bare electrodes. The requirements for stripping (duration, rate, and frequency) differ from design to design and are generally defined by the manufacturer.

The RK30 system with 12 ZBMs and 6 inverters can operate without a few ZBMs for the time it takes to perform a conditioning cycle. This should allow the system to function continuously while maintaining performance and design life. At the time of testing this feature was not enabled.

2.1. Safety Assessment

An initial safety assessment is performed on each system to identify hazards and ensure safe operation during testing. The system is inspected for fire safety, electrical safety, chemical safety, and for any other hazards that may be. This section details the results of the initial inspection.

2.1.1. Fire Safety

Zinc-bromide flow batteries generally have low energy failures. Thermal runaway is not a failure mode for this chemistry and the aqueous electrolyte is not especially flammable. During charging, hydrogen is off-gassed in some quantity and is controlled and vented to the outside of the enclosure. Hydrogen becomes combustible at approximately 4% concentration in air. As long as these vent tubes are intact and properly sealed it is unlikely for the system to be able to reach this concentration.

Even though the primary energy storage in the system is not a direct fire hazard there are many other electrical components in the system that could potentially present a fire hazard. These components included the inverters, a small string of VRLA batteries used for black-start, and two shunt resistors used for dissipating energy during a strip cycle. The system had no fire detection or suppression system installed.

2.1.2. Electrical Safety

A distinct advantage of zinc-bromide flow batteries is that they be depleted to zero energy without causing damage. This means that they can be worked on and around without presenting an electrical hazard. The system had several exposed buses behind a Plexiglas shield that could not be touched during normal operation. However, during

the course of testing a technician, after proper Lock-Out-Tag-Out, had to go into the tight space past the shield, potentially being exposed to the bus voltage.

2.1.3. Chemical Safety

As with any battery the operator should not be exposed to the electrolyte of a zinc-bromide battery under any normal operational circumstances. If exposed however, the aqueous electrolyte in a zinc-bromide battery has two potential hazards: acidity, and off-gassed bromine. The electrolyte is acidic and can cause irritation to skin and damage to eyes if exposed. The system should be equipped with a portable eyewash station and a sufficient quantity of water to accommodate skin and eye washing in the case of an exposure

Off-gassed bromine, in high enough concentrations, can cause dizziness, lightheadedness, and under extreme conditions, fainting. Properly ventilation in the area of a spill is the best way to address and mitigate this hazard. Before any cleaning or repair is attempted, both ends of the enclosure should be opened and the system should be allowed to air out for several minutes. Anyone experiencing the symptoms listed above should be removed from the area and allowed to rest.

Operators should be familiar with the Materials Safety Data Sheet (MSDS) and should consult it if visible damage is observed that exposes the personnel to the electrolyte.

2.1.4. Other

During setup and commissioning the system presented a pinch hazard as the ZBMs had to be loaded into a very tight space by forklift with operators guiding it into position. A misplaced hand or mistake by the forklift operator could result in an injury. The system should be inspected for damage that may have occurred during shipment. The inside should be kept clean of dust and debris.

3. TEST RESULTS

This section discusses the results of the tests performed by Sandia on the Raytheon/KTech RK30 Energy Storage System.

3.1 Capacity Test

Capacity test is performed to determine the energy capacity and the round trip energy efficiency. The test begins by charging the energy storage system from the Sandia electrical grid to 100% SOC using the manufacturer's recommended charging scheme. As many battery systems limit their usable SOC range to prolong design life, this 100% SOC is defined as the top of the usable range defined by the manufacturer. A power command is then sent to the energy storage system to discharge at rated power rating or 60kW, lesser of the two, into the Sandia electrical grid and to continue providing power until the system can no longer provide power and must be charged; again this limit is defined by the manufacturer. Amp-hours DC and kilo-watt-hours AC will be recorded during this time. The energy storage system will then be charged back to the 100% SOC from the Sandia electrical grid while amp-hours and kilo-watt-hours are recorded. This test will be repeated up to four times with a rest period, recommended by the manufacturer, between each test. This allows the system to reach steady state operation and provides a measure of repeatability.

3.1.1 Capacity Test Results

The system has 120 kWh installed ZBMs which are rated for full capacity cycles. Note that these cycles start with a full charge instead of a full discharge because it provides a better state to return to after the cycle to determine efficiency. The system's capacity was difficult to test for three reasons: inconsistent operation at the time of testing, unclear definition of 100% SOC, and cycle performance time (approximately 16 hours). The power output profile from one cycle is shown in Figure 2 with the positive value representing the flow of power from the energy storage system to the electric grid. In this test the inverters were commanded to charge the batteries overnight such that personnel could be present for the discharge portion in the morning. However, one or more inverters performed inconsistently (coming on and off line) for some of the charging time. This unstable operation was observed more at higher power levels, accordingly a set point of 22kW was chosen. This correction resulted in the system not achieving a full charge.
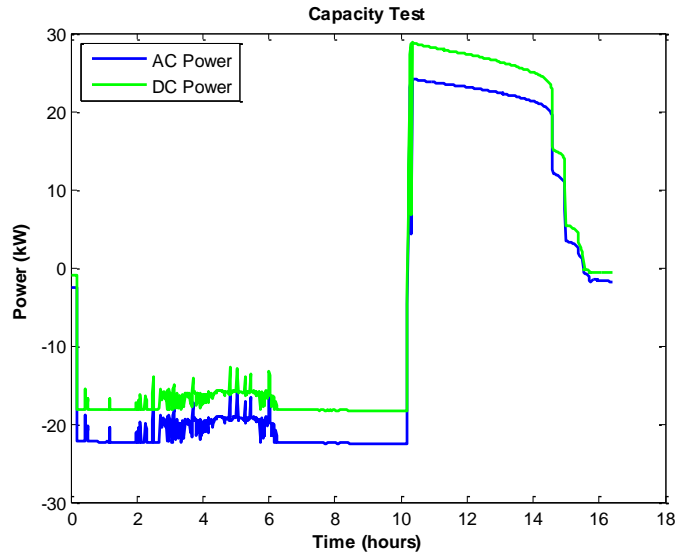
Figure 2 Max Power Capacity Test

Data from the power output profiles were integrated to calculate the values shown in Table 1.

Table 1 Capacity Test Results

Energy Discharged	= 104 kWh
Energy Charged	= 216 kWh
Max Power, Energy Efficiency	= 48.1%
Standby losses*	= 2.5kW

*Recorded during rest periods between tests

The intermittent inverter operation is not ideal for a capacity test but this is the closest the system came to a full energy cycle during the testing period. It is likely that the intermittent failure would negatively affect efficiency in some way. Appendix A contains data from three near-full energy cycles performed by the manufacturer after the testing period was completed.

3.2 Commanded Response Test

Command response testing was performed to determine the control system characteristics of the inverter. A commanded change in real power is a measure of the rate that a system can change the magnitude of the current it supplies. Before each test is performed, the energy storage system is charged from the Sandia electrical grid to an operational SOC which allows the system to both charge and discharge from the grid without hitting energy limits. A real power command is sent to the energy storage system to provide 25% of rated real power or 15kW, lesser of the two. Sandia will record the event until the energy storage system reaches a steady state point. This test will be repeated an additional two times to ensure accuracy and repeatability. As the energy storage system was tested with a 25% rated real power, or 15kW command, the system will be tested for a real power load step of 50% rated power or 30kW, 75% rated

power or 45kW, and 100% rated power or 60kW. Then a real power command is sent to the energy storage system to consume 25%, 50%, 75% and 100% of rated charge power. As many energy storage devices cannot be charged as quickly as they can be discharged, these power set points may represent a different range than the charge portion of testing.

Reactive power will also be tested, although somewhat differently. A commanded change in reactive power is a measure of the rate that a system can change the magnitude and phase of the current it supplies. As the real power steps have already been tested, the system's capability to change the magnitude the current waveform has been determined. To determine the system's capability to change the phase of the current waveform the system is subjected to commanded changes in reactive power.

3.2.1 Commanded Response Test Results
The system has a 30 kW rating, however when commanded a 30 kW charge or discharge command, the inverters began to ramp up only to trip off line. This instability could be caused by the inductance in the 75 kVA transformer used in this testing. The system was limited to 24 kW on charge and discharge to correct for this problem. Even with the correction, the inverters still tripped off on several of the higher power commands on discharge. Figure 3 shows the full test with every discharge pulse and every charge pulse, per phase. Each inverter in the system was sent a commanded step change in power set-point a total of 24 times: 25%, 50%, 75%, and 100% rated power on charge and discharge with three repetitions at each level.

Figure 3 Commanded Response Test Results
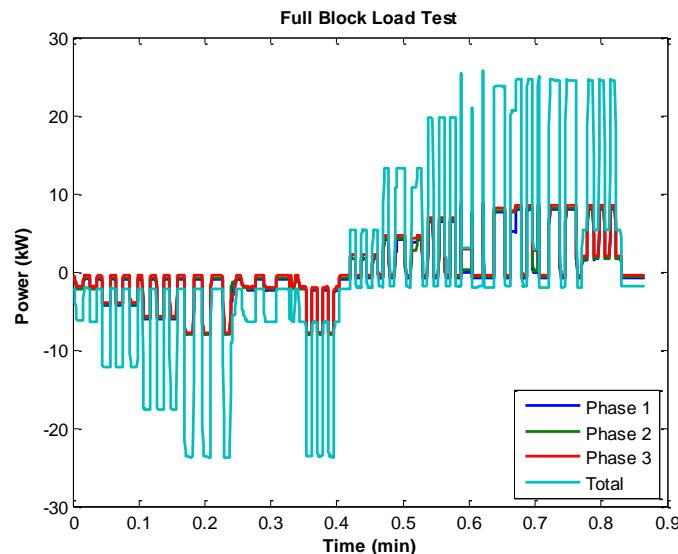
These response transients were isolated and time-shifted to a single reference starting point. Figure 4 shows each charge and discharge transient response for each phase during this test. Note that the multi-step responses in Figure 4 could have been caused by a command not being recognized by one or more inverters. The command is sent again after 10 seconds causing the second step.
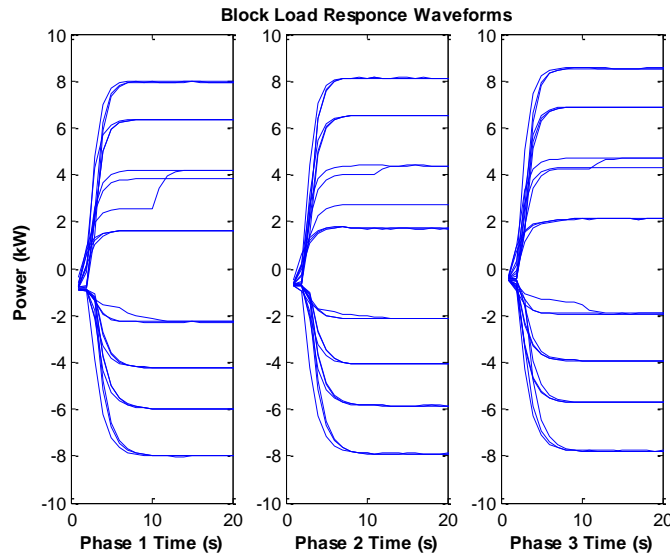
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Block Load Responce Waveforms

Figure 4 Per-Phase System Step Responses

3.3 Frequency Response Test

Frequency response tests are performed to determine if the energy storage system can be used to perform frequency regulation. Before each test is performed, the energy storage system is charged from the Sandia electrical grid to an operational SOC which allows for the system to both charge and discharge from the grid without hitting energy limits. No percent droop has been established by BCIL so the droop function will be the manufacturer's recommendation; or if no recommendation is provided by the manufacturer, a 5% droop will be tested. For the 5% droop test, a value of 61.5Hz and 58.5Hz will be used. A 480V_{LL} 3-phase 200kW utility grid simulator is hooked up to the energy storage system through a step down transformer for this test. The utility grid simulator allows for the frequency and magnitude of the voltage seen by the energy storage system to be manipulated. When the test begins, the utility grid simulator will be set for a constant voltage at 1 per unit with a frequency of 60Hz. After a few minutes, the frequency will be changed per the frequency profile shown in the results section.

As the droop function is controlled through software, this test will be a demonstration of the systems' ability to respond to changing frequency. The precise characteristic of this response would be specified for a given microgrid or a given installation and hence should be changeable.

3.3.1 Frequency Response Test Results

Figure 5 shows the test profile as the frequency is ramped up and down (Top) and the system power response (Bottom).

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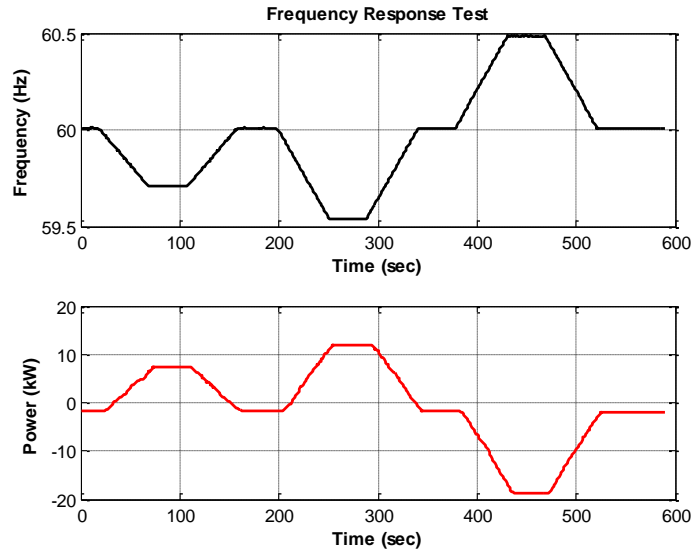
Figure 5 Frequency Response Test Results

The power per frequency (W / Hz) curve can be derived by plotting the power response against the system frequency. This curve is shown in Figure 6. Observe that the system had a smooth response within the range of frequencies tested. A slight delay in response resulted in some hysteresis. The intersection is below zero due to the standby losses of the system, and the system was limited to 15kW charge and discharge to ensure stable operation of the inverters. This test successfully demonstrated the system's ability to respond to changes in frequency.

Figure 6 Power/Frequency Curve

3.4 Voltage Response Test
Voltage response tests are performed to determine the voltage regulation functionality of the energy storage system. Energy storage systems that can perform this function allow for the voltage to remain stiff on the grid when a large induction motor such as an

environmental control unit turns on. The voltage range that the energy storage system will need to respond to is 1.05pu or 218V_{LL} down to 0.95pu or 198V_{LL}. The energy storage system will be charged to 50% SOC which is a value provided by the 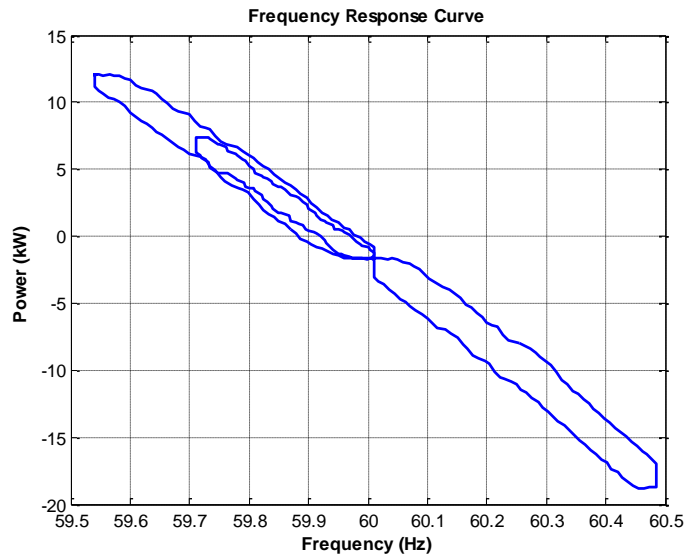manufacturer. A 480V_{LL} 3-phase utility grid simulator will be connected to the energy storage system through a step down transformer. The utility grid simulator will be set at 1.0pu V_{LL} at 60Hz when the test begins. After the system has reached a steady state, the utility grid simulator will decrease the magnitude of the voltage down to 0.95 V_{LL} at 60Hz. Sandia will record this event until the energy storage system has reached a steady state point. At this time, the utility grid simulator will increase the voltage magnitude on the system to 1.05pu V_{LL}. Sandia will record this event until the energy storage system has reached a steady state point. The test will end by the utility grid simulator returning the voltage magnitude back to the starting point of 1.0pu V_{LL}. This last event will be recorded by Sandia until the energy storage system reaches a steady state point. As the voltage response function is controlled through software, this test will be a demonstration of the systems' ability to respond to changing grid voltage. The precise characteristic of this response would be specified for a given microgrid or a given installation and hence should be changeable.

3.4.1 Voltage Response Test Results
The system did not have voltage support capability at the time of testing, therefore no data is available.

3.5 Inverter Characterization Test
THD is one measure of the quality of electric power. A "clean" 60Hz sine-wave measured on system voltage and current has 0% THD. With increasing distortions at the first harmonic (120Hz), second harmonic (180Hz), and so on, THD will increase. THD percentage is calculated by taking the magnitude of all harmonics above and including the first (limited by sample rate), adding them up and dividing them by the magnitude of the 0th harmonic (60Hz). Power electronic inverters, depending on output filtering, can have "dirty" power or "clean" power, meaning high and low THD, respectively. To measure THD, the system is commanded power outputs throughout its range of operation. THD is calculated at each step for all three phases. Data for each phase is averaged to yield the THD for each power output.

Because DC independent measurement was performed on this system the power conversion efficiency can also be calculated. Power conversion efficiency implicates how the system efficiency might change over a range of operation. It is calculated by dividing the power on the DC battery bus by the power on the AC grid connection. Note that this includes the standby losses of the system and therefore is not a direct measure of the switching losses of the inverter.

3.5.1 THD and Power Conversion Efficiency Results
Again, the system was de-rated to 24kW to ensure stable operation. Figure 8 shows the measured THD and power conversion efficiency at each step.
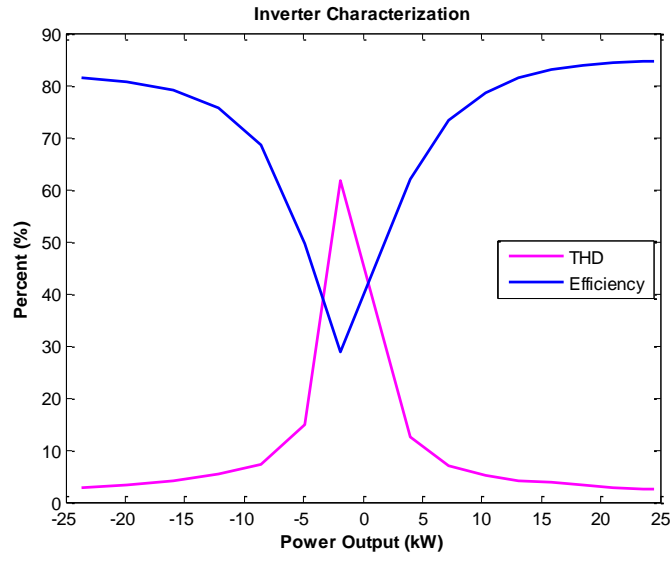
Figure 7 THD and Power Conversion Efficiency Test Results

4. ANALYSIS AND CONCLUSIONS

4.1 Performance

The data in Figure 2 show that the system has an energy performance of 104 kWh, and a round trip efficiency of 48.1% at the chosen charge rate and discharge rate of 22kW. This is a combined DC/AC efficiency as it includes the DC to AC conversion during discharge, the AC to DC conversion during charge and battery storage efficiency to return the battery to its original SOC.

From the data in Figure 4 three salient metrics can be calculated: Rise Time, Settling Time, and Overshoot Percentage. The time the response takes to rise from 10% to 90% of the steady-state value is the rise time. The settling time is the time when the error between the response and the steady-state value falls below 2% of the steady-state value. Percent Overshoot is the percent that the peak value of the response exceeds the steady state value. Note that the multi-step responses shown in Figure 4 corrupt the calculations for rise time and settling time and are consequently outliers in the data.

Figures 4, 5, and 6 show the measured trends of the Rise Time, Settling Time, and Percent Overshoot calculated from the responses in Figure 3.
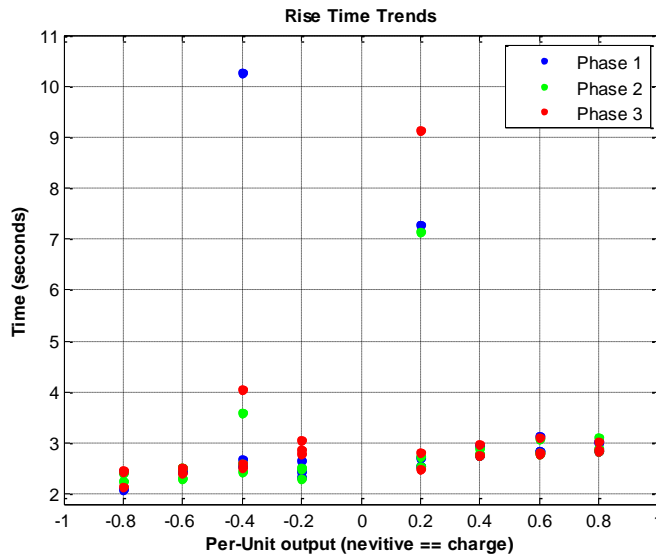

Figure 8 Rise Time
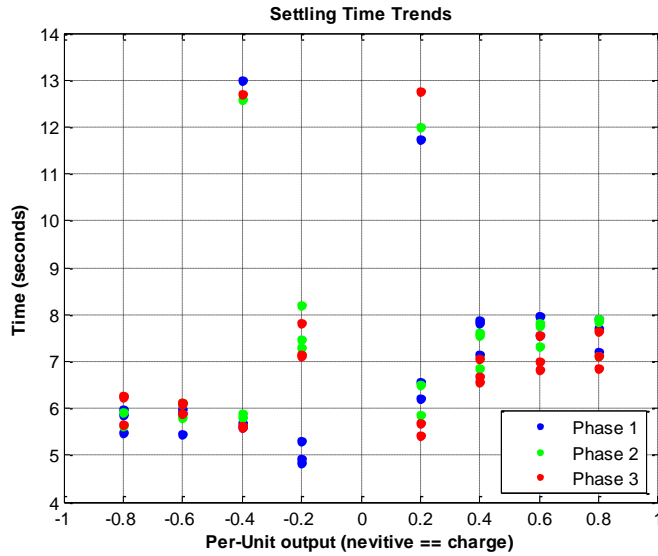
Figure 9 Settling Time
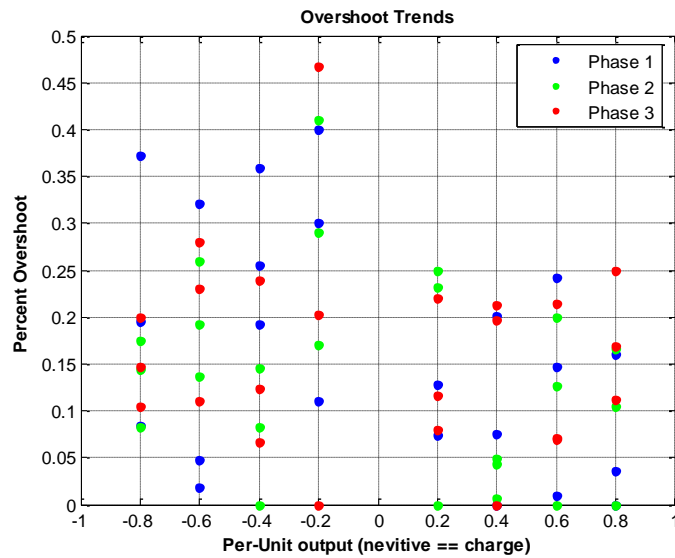
Figure 10 Percent Overshoot

This system behaved somewhat erratically with respect to what power level was stable and what power level caused the inverters to trip off line. This behavior made it difficult to assess performance in a variety of ways. Most of the time the system had a rise time of less than 3 seconds and a settling time of less than 8 seconds. It had a first order response so percent overshoot was essentially 0%.

4.2 Overall Assessment and Recommendations
The system is a prototype unit with very high potential. The ZBMs can hold and cycle a very large amount of energy. There are several concerns that should be addressed in the next stage of design including: system weight over 10,000lb, somewhat high standby losses, erratic inverter behavior, and control program maturity.

The system weight is partially addressed by the shipment of the ZBMs separately to the container. While this is not ideal for easy movement of the device in an FOB, as they are often limited to 10,000lb forklifts, it does allow the system to be moved around by a smaller forklift in some circumstances. The standby losses for the system could be mitigated by shutting off and disconnecting inverters not in use. The control program has dynamic access to each inverter's power state and output and hence the system could easily be optimized to reduce standby losses. Additionally, individual control of inverters could also be utilized to correct for load imbalance on a microgrid.

During the course of testing a component in the system caught fire and testing was stopped. See Appendix B for the root cause inspection. As the component was primarily used in startup the system continued to function without fault or warning until the smoke was noticed by a passerby. It is recommended that a fire detection system be installed to warn operators and personnel in the area of a fire. Additionally, it is recommended that the fire detection system includes an automated response to interrupt the AC and DC circuits, and that an externally accessible fire extinguisher is installed. As the fire occurred in a minor section of the system repair and recovery took less than a day after which testing could resume.

It was determined after the testing period that the grid connection being used for testing had particularly high impedance which can change the dynamic stability widow for inverters. This could explain the erratic inverter behavior if the impedance of the line put the inverters to the very edge of stable operation. If this were the case the control parameters in each inverter's in firmware would have to be recalibrated or the inverters themselves would have to be replaced with more broadly stable inverters. Systems used in microgrids should have extremely robust stability characteristics but these parameters are difficult to change in COTS devices.

As a prototype the system performed admirably. Testing identified many design features to implement to improve performance and utility. Even the fire, as minor as it was, brought with it the knowledge for how to prevent it in the future. The system design is being refined and improved and after the proposed changes are made it is recommended that the system continues testing for potential fuel saving performance on a microgrid.

REFERENCES

1. B.Schenkman, D.Rose, D.Borneo, *"Forward Operating Base Microgrid Incorporating Energy Storage",* SANDXX-XXXX, Sandia National Laboratories, Albuquerque, NM (UR), March 2013.
2. D. Rose, S. Ferreira, "Performance Testing of Zinc-Bromine Flow Batteries for Remote Telecom Sites" Battcon 2013 stationary battery conference, May 2013

APPENDIX A: POST TESTING CAPACITY CYCLES

Because of time constraints the system was not able to complete a full energy cycle during the test period that did not include some erratic inverter behavior. Once returned to Raytheon/KTech's lab, the system was put through three post testing cycles to confirm system performance and stable operation ability. The data was collected by a PQube power quality meter. Data from this meter was validated against Sandia's data acquisition system during the testing period. However, these data do not come from the Sandia National Laboratories and therefore are informative, for the purposes of third party validation.

Figure 11 shows three post testing cycles super imposed on each other on an relative time scale. Observe the stable operation of the inverters at a lower charge rate then during the testing period. The two spikes that in cycles 2 and 3 can be attributed to the control timer resetting at midnight and momentarily causing a drop in power set point. This artifact could be corrected in the control program.
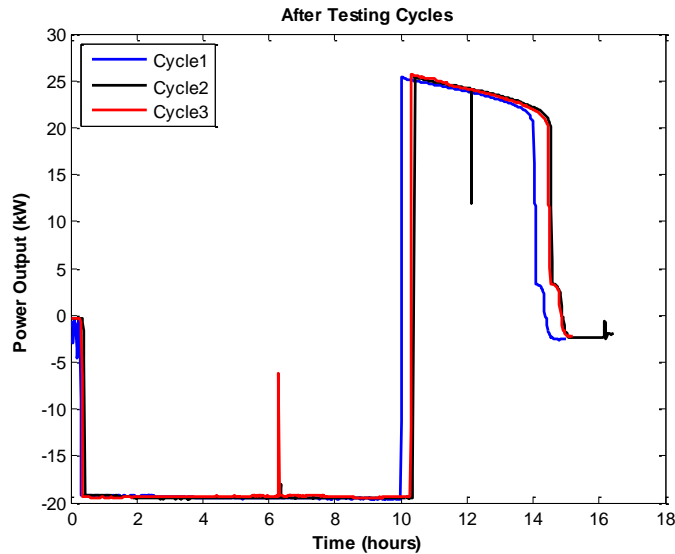
Figure 11 Figure Post Testing Capacity Cycles

These cycles had an energy performance of 97-100 kWh and efficiencies between 49.6% and 50.3%. This improvement in efficiency is consistent with more reliable inverter operation.

Table 2 Post Testing Cycles

	Cycle 1	Cycle 2	Cycle 3
Energy Discharged	= 97 kWh	= 99 kWh	= 100 kWh
Energy Charged	= 195 kWh	= 198 kWh	= 198 kWh
Max Power, Energy Efficiency	= 49.6%	= 50.1%	= 50.3%

APPENDIX B: COMPONENT FIRE, ROOT CAUSE INSPECTION

On May 6th, the system was started and given a low power charge command. It came to the attention of the technicians on site that smoke was emanating from the top vent of the system. The system was shut down and the fire put out with a hand held, class C fire extinguisher. This section details the evidence collected and the conclusions reached concerning the cause of the fire.

Figure 12 shows the scene of the fire within the system. Three components are visible that each could have been the fire's source: DC power supply, Power Resistor, and Lead Acid Battery String. The white dust is from the fire extinguisher. The most damaged component appears to be the Power Resistor. These components were removed from the system and placed in a staging area for further inspection.

Figure 12 Observed Source of Fire

Figure 13 shows the DC power supply after its removal from the system and disassembly. Observe the significant blackening of the internal components. There were no ruptured components or concentrated burn marks. Also observe that the intake fan was the most damaged component followed by the board surface directly below it. This suggests the fire started outside of the power supply and was pulled into it by the intake fan. As the power supply was mounted in the system above the power resistor and battery string these observations are consistent with the fire starting at one of those two components.

Figure 13 Discounted Source of Fire (DC power supply)

Figure 14 shows the battery string and the power resistor outside after they were removed from the system. Observe that the damage to the batteries is limited to the size of the power resistor. Observe also the thorough charring of the resistor while the top of the battery string was only partially melted. The power resistor was mounted in the system directly above the batteries using plastic mounting brackets. These observations suggest a scenario in which the power resistor overheated and caught on fire, melted through its mounting brackets, and fell on top of the battery string.

Figure 14 Resistor Fire Fell on Batteries

It was determined that the root cause of the fire was the power resistor being incapable of handing the current that was put through it. Whether the resistor was undersized, had a manufacturing defect, or if there was some other fault in the system that lead to higher than normal currents was beyond the scope of this inspection. It is recommended that future designs include in-line fusing or circuit breakers designed to protect all power circuitry.

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