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Test Report: GS Battery, EPC Power HES RESCU

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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. GS Battery and EPC Power have 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 GS Battery, EPC Power HES RESCU.

ACKNOWLEDGMENTS

This work was funded by the Department of Energy Office Of electricity delivery & energy reliability under Dr. Imre Gyuk.

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TABLES

NOMENCLATURE

%OS	Percent Overshoot
BCIL	Base Camp Integration Laboratory
DETL	Distributed Energy Technology Lab
DOE	Department of Energy
ESS	Energy Storage System
ESTP	Energy Storage Test Pad
FOB	Forward Operating Base
GSB	GS Battery (of GS Yuasa)
HES	Hybrid Energy System
PPE	Personnel Protective Equipment
RESCU	Rugged Energy Storage Containment Unit
SOC	State of Charge
SNL	Sandia National Laboratories
VRLA	Valve Regulated Lead Acid

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 the fossil fuel consumption and to ultimately decrease the use of military convoys. Energy storage vendors made available 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. Testing at Sandia National Labs includes a capacity test, block loading 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. GS Battery and EPC Power provided Sandia their HES RESCU (Hybrid Energy System, Rugged Energy Storage Containment Unit) for testing which the results are documented in this report.

2. TECHNOLOGY DESCRIPTION

The GS Battery, EPC Power HES RESCU uses 36 SLX246-12 VRLA 12V batteries and a single 105kVA three phase inverter (limited to 60kVA by the battery string) supplied by EPC Power to sink, store, and supply electrical energy. The battery string has a nominal voltage of 432V and can supply up to 246Ah before being fully depleted. The VRLA batteries were chosen for their cost and could be replaced by Li-Ion for increased performance and decreased weight. The inverter, originally designed as a motor drive for heavy EVs, has a liquid cooling loop to dissipate heat through an air cooled manifold. Figure 1 shows the system as it arrived at SNL in July of 2013.

Figure 1 GS Battery, EPC Power energy storage system delivered to Sandia

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 present in the system. This section details the results of this initial inspection.

2.1.1. Fire Safety

VRLA batteries have two modes of failure with respect to fire potential: thermal runaway and hydrogen buildup. The system comes equipped with both a fire detection system and a hydrogen detection system. In case of a fire or hydrogen buildup the system self-isolates and produces auditory and visual alarms warning operators and bystanders of the hazard. Additionally, the system has a fire extinguisher of the proper class installed to aid in emergency response.

2.1.2. Electrical Safety

The system employed many safe wiring practices including the use of rated Anderson Connectors for disconnecting the battery string during shipment. The system was tested well-grounded (less than 1 Ohm from system ground to ground rod lug) to prevent static buildup. An external E-Stop button was installed to allow operators to break both AC and DC circuits in case of an emergence without being exposed to any hazards that may be present in the system.

Above head height and set back from the front of the battery rack was one area of exposed contactors. This exposes operators to the battery string voltage when operating the system's DC breaker (requiring the use of PPE when doing so). It is recommended that a safety glass shield be installed to cover the exposed busses to remove the hazard. All other system voltages were sufficiently isolated.

2.1.3. Chemical Safety

The batteries are AGM (Absorbent Glass Mat) type VRLA. In AGM batteries the electrolyte is absorbed in a sponge mat that keeps it from spilling in case of a simple rupture. If cleanup is necessary due to extensive damage, the Materials Safety Data Sheet (MSDS) should be consulted.

2.1.4. Other

The system should be inspected for damage that may occur 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 GS Battery and EPC Power HES RESCU.

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 106.3 kWh (at 20 hour discharge rate) installed VRLA lead acid batteries. At 60kW the rated capacity of the batteries is reduced to 66kWh (1.1 hours). The system operates from 10%-100% SOC (recommended by GS Battery); the rated system capacity is reduced to 59.4 kWh. To validate this rating and to determine efficiency and standby losses, the system was fully charged and then a 60kW power command was sent to the energy storage system to discharge as long as possible. This procedure was repeated three times on three consecutive days. The power output profiles are shown in Figure 2 with the positive value representing the flow of power from the energy storage system to the electric grid.

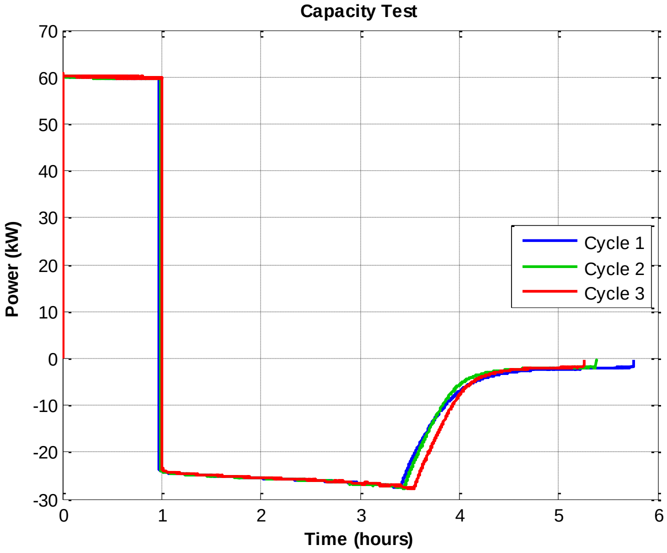


Figure 2 Max Power Capacity Test

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

Table 1 Capacity Test Results

	Cycle 1	Cycle 2	Cycle 3
Energy Discharged	57.8 kWh	58.4 kWh	59.8 kWh
Energy Charged	76.9 kWh	75.3 kWh	76.8 kWh
Max Power, Energy Efficiency	75.1%	77.6%	77.9%
Standby losses*	452 W	431 W	414 W

*recorded during rest periods between tests

The standby losses include Inverter losses, FACP/H2 sensor controller, 24VDC power supplies (for inverter control power, cooling loop pump, HX fans, LED lighting), and Exhaust Fans.

3.2. Command 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. Command Response Test Results

The EPC Power control program has a ramp rate limit input to allow operators to control how fast or slow the system responds. To test the functionality of this feature, the command response test was repeated twice: once with the limit imposed at 6kW/sec, and once with the limit removed to determine the maximum ramp rate. Figure 3 shows the full test with the ramp rate limit imposed, with every discharge pulse and every charge pulse, per phase.

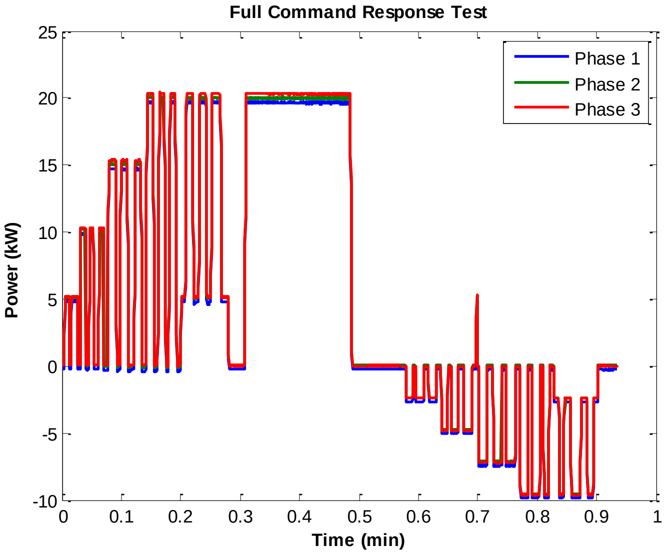


Figure 3 Full Command Response Test 6kW/sec Ramp Rate Limit

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. Observe the ramp rate limit effectively and consistently restricting the response of the system.

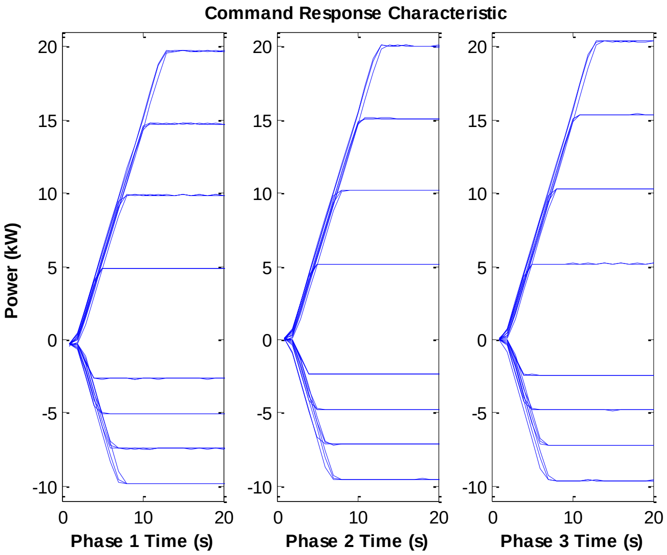


Figure 4 Per-Phase System Step Responses 6kW/sec Ramp Rate Limit

Figure 5 shows the full test with the ramp rate limit removed, with every discharge pulse and every charge pulse, per phase.

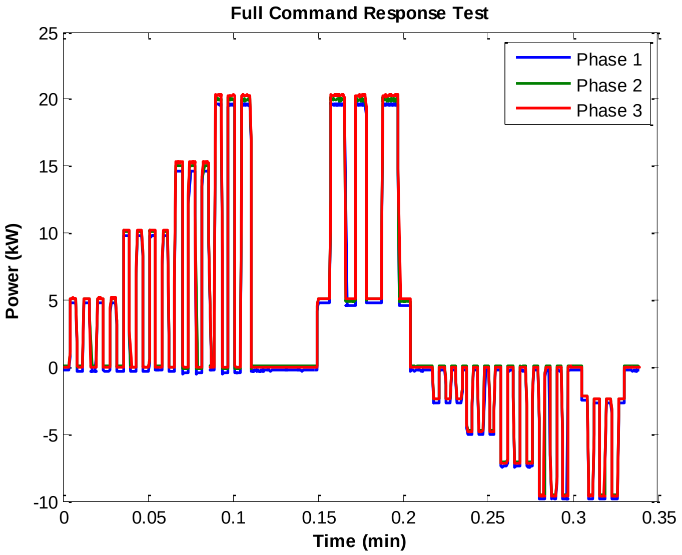


Figure 5 Full Command Response Test No Ramp Rate Limit

These response transients were isolated and time-shifted to a single reference starting point. Figure 6 shows each charge and discharge transient response for each phase during this test. Observe that the system reaches its set point at a much faster rate than in the ramp rate limited test with no noticeable increase in overshoot or steady state error. As the sample-frequency for these tests is 1Hz the true maximum response rate needs to be measured using a waveform capture.

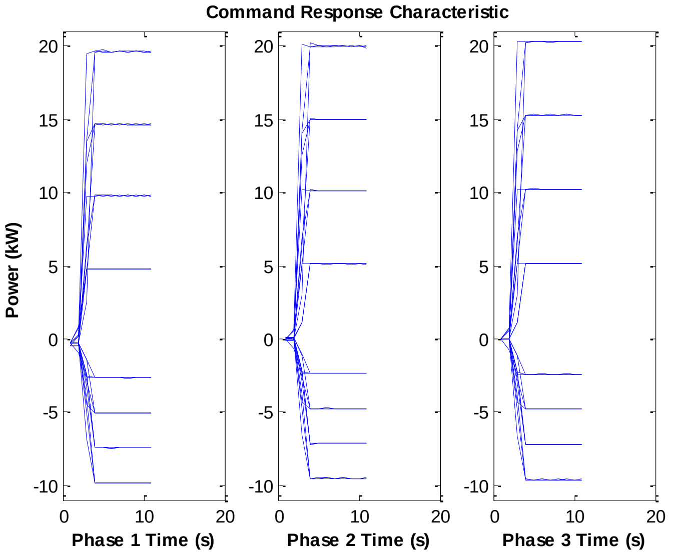
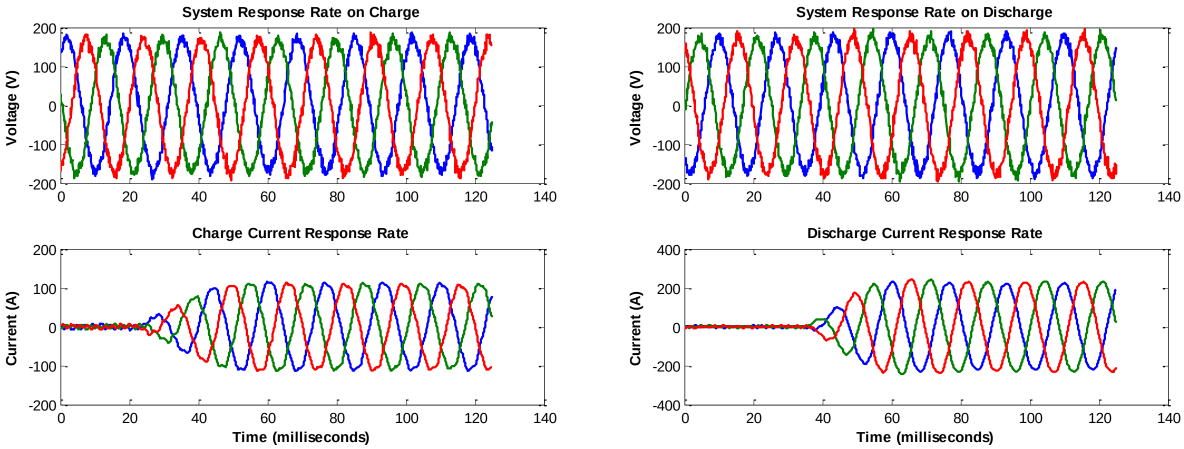


Figure 6 Per-Phase System Step Responses No Ramp Rate Limit

Figures 7 (a) and (b) show the inverter's waveform response rate at a sample-frequency of 26kHz. The higher resolution data show a considerably faster response.



(a) (b)

Figure 7 System Waveform Commanded Response on Charge (a) and Discharge (b)

Further analysis of these results can be found in Section 4.1.

3.3. Frequency Response Test

Frequency response test is 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 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 manufacturer's recommendation or, if no recommendation by manufacturer is given, 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 7 shows the test profile as the frequency is ramped up and down (Top) and the system power response (Bottom).

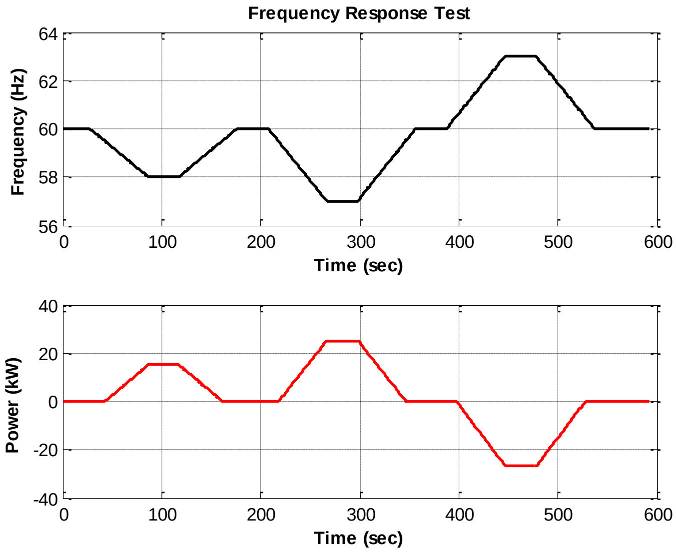


Figure 8 Frequency Response Test Results

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 8. Observe that the system had a smooth response within the range of frequencies tested. Very fast system response resulted in nearly zero hysteresis. The system was limited to 25kW charge as this is the system's approximate limit on charge. In the frequency and voltage response bonus test, the system is observed to respond up to its full discharge rating. This test successfully demonstrated the system's ability to respond to changes in frequency.

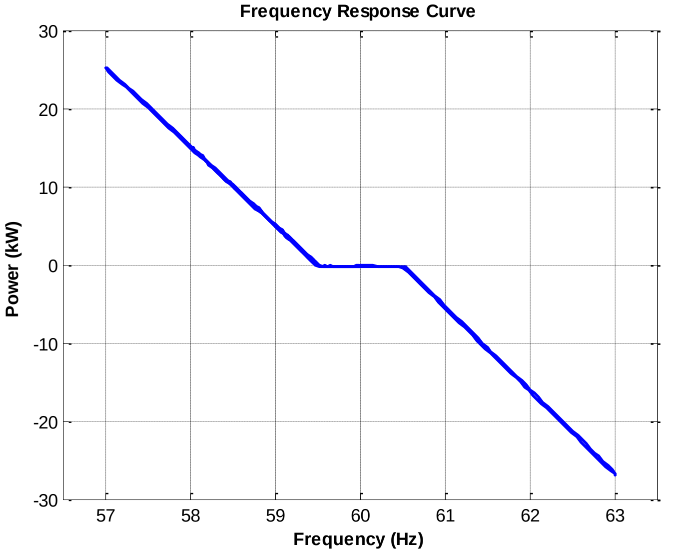


Figure 9 Power/Frequency Curve

3.4. Voltage Response Test

Voltage response test is 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}. 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 is normally connected to the electric grid or grid simulator through a 75kVA, 208-Y/480-Δ transformer. For this test the system had to be connected directly to the grid simulator because as the system responded to changes in voltage it would correct the voltage on the low side of the transformer into its dead-band (effectively canceling out the commanded change in voltage). The direct connection to the grid simulator acted as a stiff enough voltage source to perform tests. Figure 9 shows the test profile as the mean of the phase voltages is ramped up and down (Top) and the system reactive power response (Bottom).

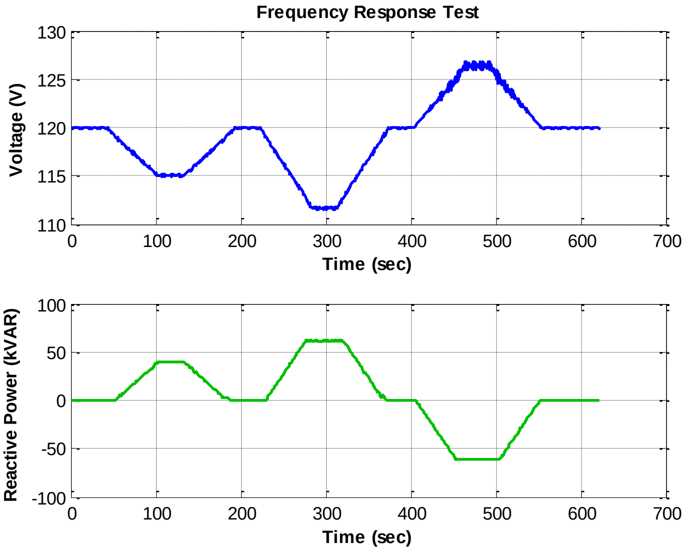


Figure 10 Voltage Response Test Results

The reactive power per volt (VAR / V) curve can be derived by plotting the reactive power response against the mean of the phase voltages. This curve is shown in Figure 11. Observe that the system had a smooth response within the range of voltage tested. Very fast system response resulted in nearly zero hysteresis. The system was allowed to operate to the full extent of the inverters limits (60kVA). This test successfully demonstrated the system's ability to respond to changes in voltage.

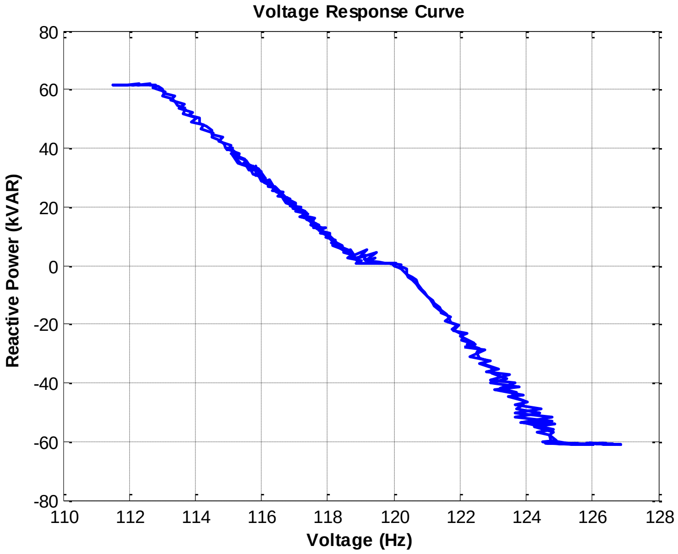


Figure 11 Reactive Power / Voltage Curve

3.5. Frequency and Voltage Response Bonus Test

As this system successfully demonstrated its capability to respond to changes in both frequency and voltage separately, an additional test was devised to demonstrate the system simultaneously responding to changes in both frequency and voltage. The grid simulator was programed with the following steps.

- Begin with the system at rest (120VAC, 60Hz)
- Ramp to a lower voltage (112VAC, 60Hz)
- Ramp to a lower frequency (112VAC, 57Hz)
- Ramp to a higher voltage (128VAC, 57Hz)
- Ramp to a higher frequency (128VAC, 63Hz)
- Ramp to a lower voltage (112VAC, 63Hz)
- Ramp to nominal frequency (112VAC, 60Hz)

In this way the system is pushed to the limits of its response to each individual dimension.

3.5.1. Frequency and Voltage Response Bonus Test Results

Figure 12 shows the test profile as the: 1. Frequency is ramped up and down (Top), 2. The mean of the phase voltages is ramped up and down (Middle) and 3. The system real and reactive power response (Bottom). Observe that the voltage profile does not match the defined profile. This is because as the system responds to changes in frequency with real power it affects the local voltage as a function of the line impedance. This real power output distorts the voltage input the system is responding to.

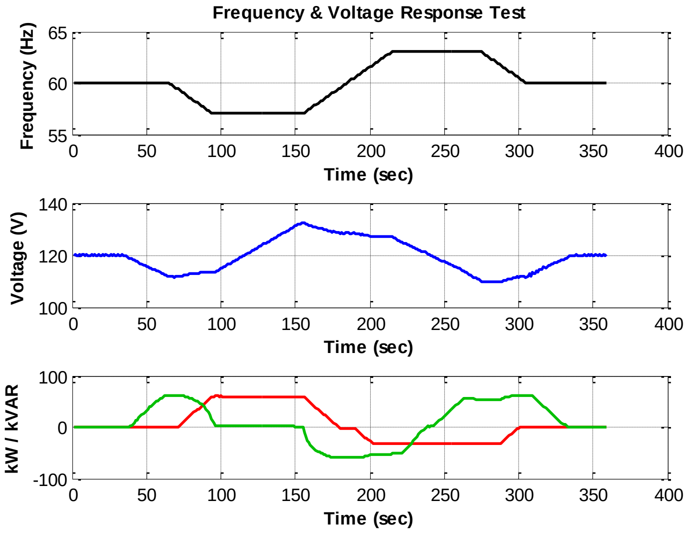


Figure 12 Frequency and Voltage Response Bonus Test Results

The real power per frequency (W / Hz) and the reactive power per volt (VAR / V) curves can be derived by plotting the responses against their respective inputs. These curves are shown in Figure 13. Note that the system preferentially responds to frequency when the VA limit of the system (60KVA) is reached. This along with distorted local voltage causes an unintuitive ideal curve for the voltage response. Observe that the W / Hz curve is very smooth with almost no hysteresis. The reactive power response of the system follows the ideal path closely meaning that the system is behaving as expected. The small error observed is likely a result of the physical wiring distances between the inverter terminals, SNL data acquisition system, and the grid simulator. The voltage losses over these lines at maximum power could account for a difference in measured voltage and hence calculated output set point. This test successfully demonstrated the system’s ability to respond to simultaneous changes in both frequency and voltage.

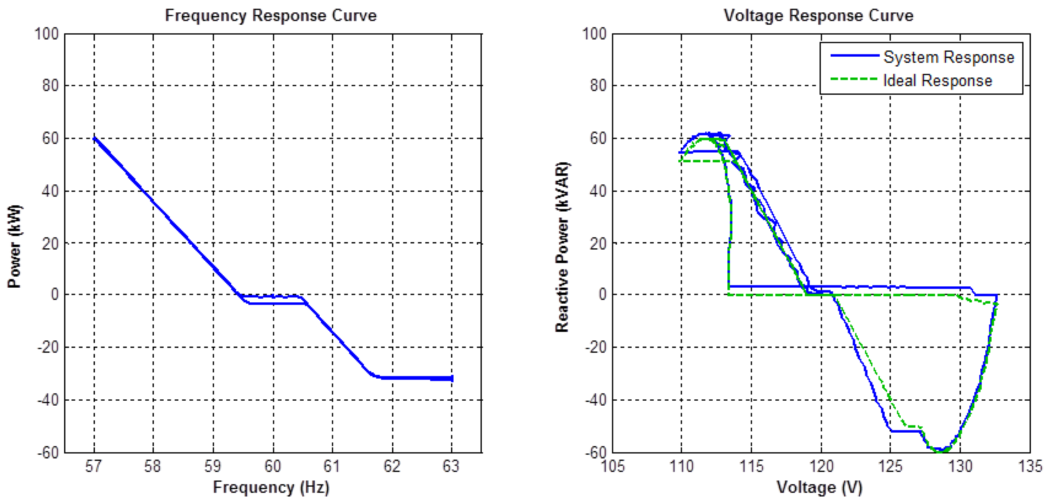


Figure 13 Real Power / Frequency (left) and Reactive Power / Voltage (right)

3.6. Inverter Characterization Test

THD is one measure of the quality of electric power. A “clean” 60Hz sin-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 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. The data for each phase are 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 gives some sense for 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 hence is not a direct measure of the switching losses of the inverter.

3.6.1. THD and Power Conversion Efficiency Results

Figure 14 shows the measured THD and power conversion efficiency at each step. At full discharge the inverter is just over 95% efficient with THD under 2%.

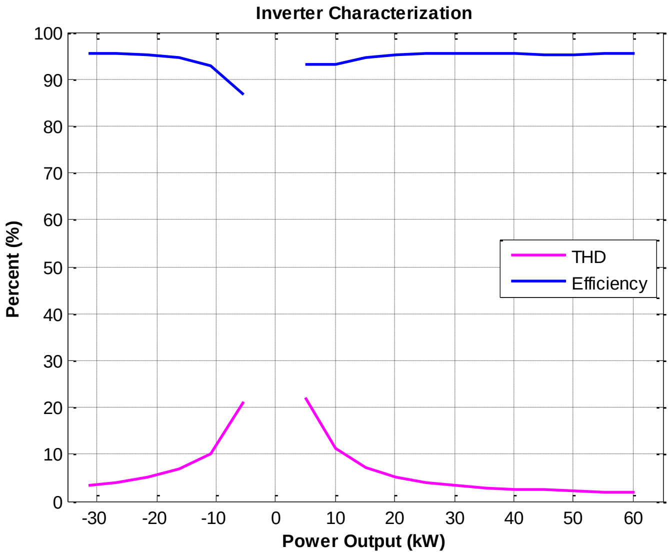


Figure 14 THD and Power Conversion Efficiency Test Results

Further analysis of these results can be found in Section 4.1.

4. ANALYSIS AND CONCLUSIONS

4.1. Performance

The data in Table 1 show that the system has an average energy performance of 58.6 kWh, and an average round trip efficiency of 76.8% at a the chosen charge rate and discharge rate of 60kW. 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 Figures 4 and 6 three salient metrics can be calculated: Rise Time, Settling Time, and Percent Overshoot. The rise time is the time the response takes to rise from 10% to 90% of the steady-state value. 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 hence outliers in the data.

Figures 15, through 17 show the measured trends of the Rise Time, Settling Time, and Percent Overshoot calculated form the responses in Figure 3.

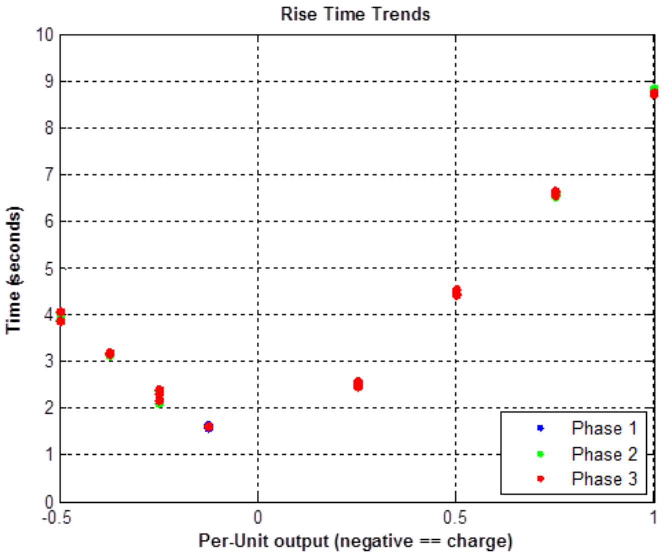


Figure 15 Rise Time, 6kW/sec Ramp Rate Limit

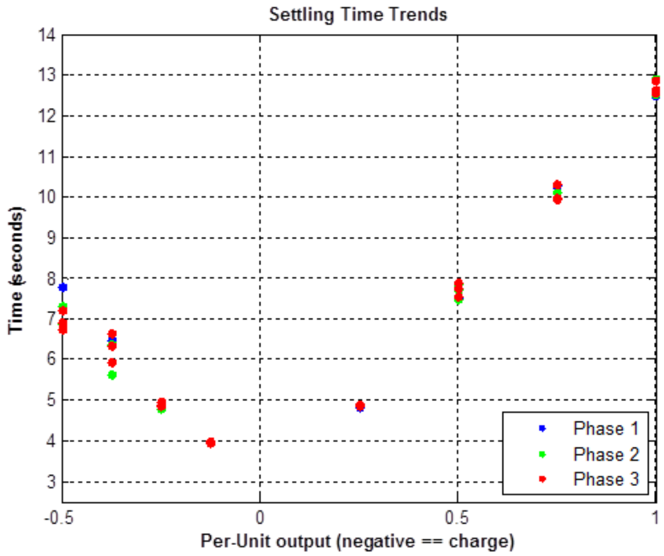


Figure 16 Settling Time, 6kW/sec Ramp Rate Limit

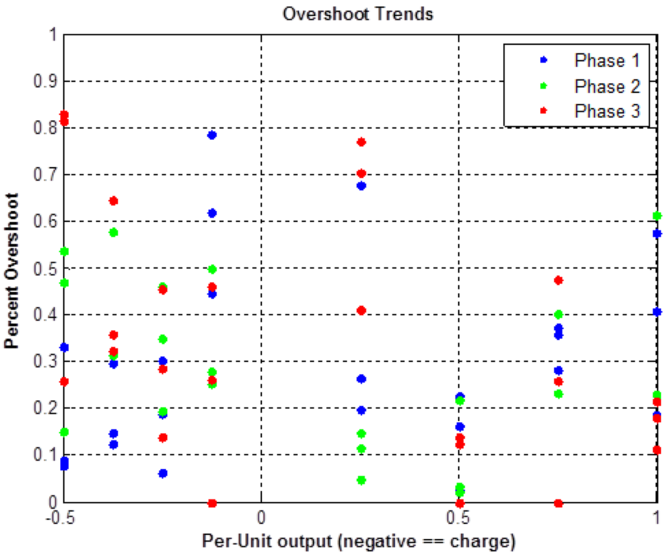


Figure 17 Percent Overshoot, 6kW/sec Ramp Rate Limit

Power can be calculated form the voltage and current waveforms in Figures 7 (a) and (b). Each phase voltage and current are multiplied and then added together to yield the instantaneous system power. Figure 18 shows power as a function of time as the system responds to a commanded charge and commanded discharge. The rise time is still computed as the time the response takes to rise from 10% to 90% of the steady-state value (60kW on discharge and 30kW on charge). Shown in red and green are the10% and 90% window borders for both charge and discharge. On discharge the system has a rise time of 16ms in which time it changes its power output by 48kW. This equates to the system possessing the ability to supply a power ramp rate of 3 MW/sec

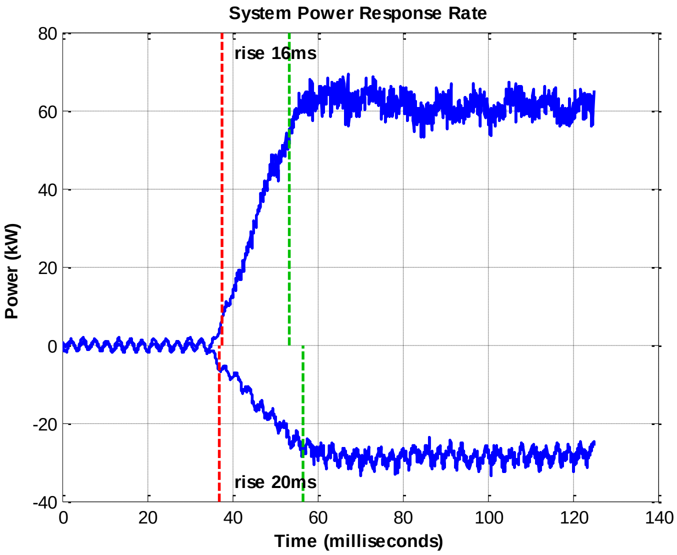


Figure 18 Rise Time No Ramp Rate Limit

These tests successfully demonstrate the system's ability to control its ramp rate. When the 6kW/sec ramp rate is implemented, the calculated rise time matches 6kW/sec closely. With the limit disabled the rise time is consistently less than 20 milliseconds regardless of set point magnitude. In all cases the percent overshoot was less than 1%.

4.2. Overall Assessment and Recommendations

The HES RESCU system is a high performance prototype designed to operate in harsh conditions safely and reliably. The system was able to quickly perform each test leaving time to perform several additional tests including the second command response test and the Combined Frequency and Voltage Response Test.

During commissioning, it was discovered that the high impedance transformer being used for 208V 3-Phase testing was keeping the battery system's inverter from being able to operate normally. The control algorithm that allows the system to synchronize with the electric grid had been moved into a region of instability. The inverter manufacture was able to supply updated firmware to widen the window of stable operation which fixed the problem. After the issue was resolved the inverter behaved stably and consistently through testing.

The Lead Acid batteries are a cost effective means of demonstrating the technology and fielding a system quickly but in the future the unit could be designed with a Li-Ion battery string for improved performance and lighter weight. It is recommended that GS Battery install a protective shield over the DC breaker to protect operators from being exposed to hazardous voltage.

The installed hydrogen sensor can falsely identify a hydrogen buildup if moisture is present in the system. This can happen any time the system is turned off for an extended period of time. The sensor initialization procedure is meant to remove moisture form the system and hence prevent false alarms.

The system’s ability to save fuel in a FOB microgrid has yet to be assessed. Its efficiency and discharge power ability could be advantageous while its lower charge power ability could be a disadvantage. Other factors in implementation include its adjustable response rate, very low harmonic distortion, and the high degree of safety in design and operation. As this is a prototype unit any issues could be addressed in future designs. Further analysis, testing, and demonstration are necessary to determine the effect of these factors on fuel savings and the potential for overall installation success.

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.

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