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Test Report: Princeton Power Systems Prototype Energy Storage System

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Test Report: Princeton Power Systems Prototype Energy Storage System

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Abstract

The Department of Energy Office of Electricity (DOE/OE), Sandia National Laboratory (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 comprised of lead acid, lithium-ion or zinc-bromide. Princeton Power Systems has developed an energy storage system that utilizes lithium ion phosphate batteries to save fuel on a military microgrid. This report contains the testing results and some limited analysis of performance of the Princeton Power Systems Prototype Energy Storage System.

ACKNOWLEDGMENTS

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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
PPE	Personal Protective Equipment
SOC	State of Charge
SNL	Sandia National Laboratories

1. INTRODUCTION

Department of Electricity (DOE/OE), Sandia National Laboratory (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 comprised 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 performance and design and provide recommendations for each Vendor. Princeton Power Systems provided Sandia their Prototype Energy Storage System for testing (the results of which are documented in this report).

2. TECHNOLOGY DESCRIPTION

The Princeton Power Prototype Energy Storage System utilizes a lithium ion phosphate battery bank with a rating of 100kW and 60kWh. The installed inverter in the system is composed of a 60Hz three phase inverter rated at 480Vac and a power rating of 100kW. This testing is limited to 60kW and therefore this system may be at a disadvantage when compared to systems that were designed to the 60kW specification. The voltage is stepped down through a 480Vac delta to 208Vac wye transformer rated at 112kVA. The DC bus is rated from 280Vdc – 600Vdc with a maximum output current of 285Adc or 95kWdc. The entire system is housed inside a tricon container which includes the power electronics, batteries, transformer, and fans. This system also has inputs for renewables and a generator for charging the energy storage system while maintaining a stiff electrical grid. Figure 1 shows the system as it arrived at SNL in March of 2013.

Figure 1 Princeton 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. This section details the results of the initial inspection.

2.1.1 Fire Safety

Li-Ion batteries can potentially undergo high energy failures. The volatile nature of the chemistry requires a higher degree of monitoring and control to keep them in a safe operating range. The Battery Management System (BMS) for the system was supplied by the manufacturer to do just that. The individual cell voltages and temperatures were monitored closely. If either were to go outside of a safe operating range, the BMS would shut down the system by disconnecting the battery string. Operator intervention would be required to recover from this event. This design is consistent with preventing system fires.

The system had no fire detection or suppression system installed. In the field, it should be placed far enough away from other structures to prevent a long duration battery fire from spreading. Additionally, it is recommended that a fire detection system is installed to enable a prompt response in the case of a fire. At a minimum, a smoke alarm and externally accessible fire extinguisher would improve the fire safety of the system. Further measures may include: enabling the smoke detector to automatically isolate the AC and DC sources from the inverter, and installation of a fire suppression system to automatically extinguish fires.

2.1.2 Electrical Safety

In the US, Li-Ion batteries must be shipped under very precise regulations for safety. Upon arrival, the batteries had to be loaded into the system and electrically connected in series to their full string voltage. Each 50lb module consisted of eight 3.4V cells strapped together for a full string voltage of 27.2V. The battery busses were exposed so they could be connected to the adjacent modules in the string. This means that as the modules were being installed, the exposed conductor voltage climbed higher and higher which increased both the shock and arc flash hazard to the workers. The setup and take down involved significant electrical hazard to the workers performing the operation. This hazard was mitigated per NFPA 70-E with a safety watch, PPE, and an energized work permit.

After the batteries were installed, a cover was installed to prevent incidental contact with the espoused battery terminals. This cover protected the front and top of the battery rack but not the side or back, consequently, exposed conductors could still be reached. Additionally, the external power connections were mounted on the system such that AC voltage was exposed inside the enclosure. Due to this exposure, the system had to be unplugged and tested for zero energy before it could be opened and entered.

2.1.3 Chemical Safety

The Materials Safety Data Sheet (MSDS) should be consulted if damage is observed that exposes the operator to the insides of the battery.

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 Princeton Power Prototype 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 manufacturers recommended charging scheme. 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 (whichever is less) 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 kilowatt-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 kilowatt-hours are recorded. This test will be repeated up to four times, with a rest period between each test, as is recommended by manufacturer. This allows the system to reach steady state operation and provides a measure of repeatability. Measurement is taken directly on the output of the system.

3.1.1 Capacity Test Results

The system has 82 kWh installed Lithium-Ion batteries. By limiting the voltage operating range, the system runs from 480-560 VDC string voltage (3.0 - 3.5V per cell) as recommended by Princeton Power. To test the systems usable energy 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 for as long as possible. The power output profile result is shown in Figure 2 with the positive value representing the flow of power from the energy storage system to the electric grid. The same 60kW power command was repeated three times. The power output profile in Figure 2 was selected as a representative sample.

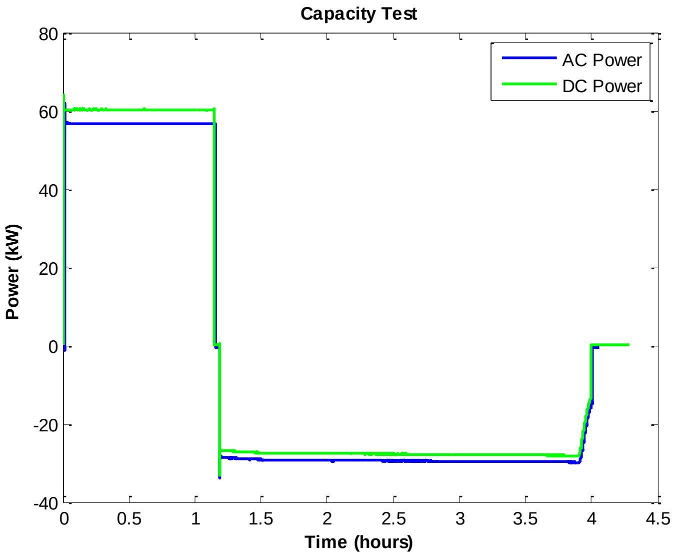

Figure 2 Rated Power Capacity Test

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

Table 1 Capacity Test Results

Energy Discharged	= 65 kWh
Energy Charged	= 82 kWh
Max Power, Energy Efficiency	= 78.7 %
Standby losses*	= 0.9-1.1 kW

*Recorded during rest periods between tests

Note that if a system is required to maintain full output (for example to keep a generator from running on a microgrid) this energy is significantly less.

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 (whichever is less). Sandia records the event until the energy storage system reaches a steady state point. This test will be conducted three times to ensure accuracy and repeatability. The energy storage system was tested with a 25% rated real power or 15kW command; similarly, 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. A real power command is then 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 tested the capability to change the magnitude of the current, the reactive steps only need to determine its ability to change the phase of the current. A commanded change in reactive power demonstrates this ability.

3.2.1. Command Response Test Results

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.

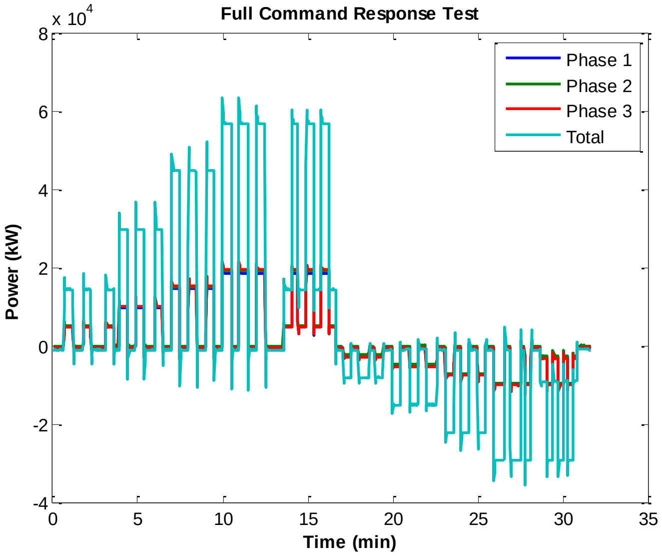

Figure 3 Command Response Test Results

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.

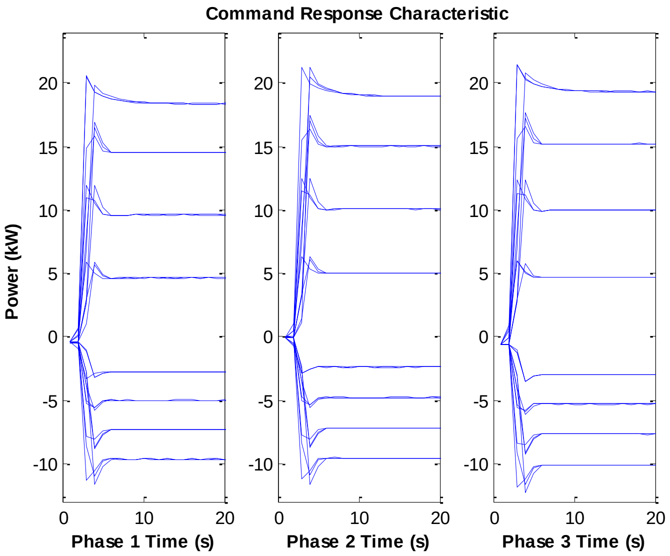

Figure 4 Per-Phase System Step Responses

The system was also able to respond to reactive power commands. This ability was successfully tested for both positive and negative reactive power to 60kW.

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 the manufacturer's recommendation; or, if no recommendation is provided by 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, it is more important that a system is able to respond to changes in frequency than to the specific response. The shape of this curve would be specified for a given microgrid or a given installation and therefore 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 shows the system power response (Bottom).

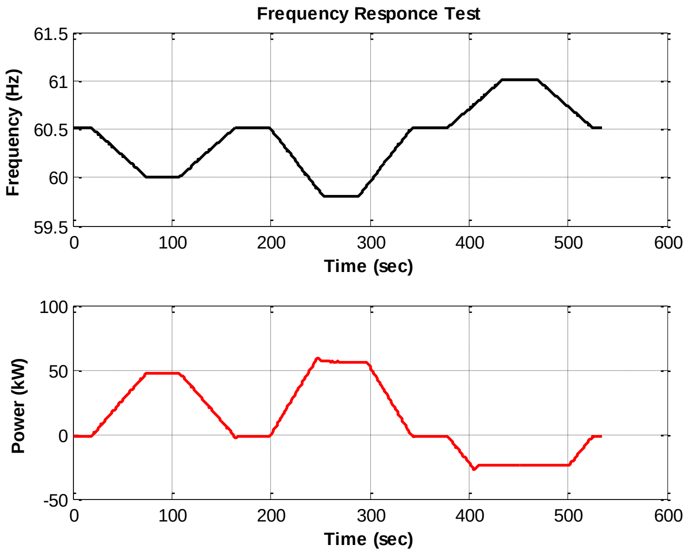

Figure 5 Frequency Response Test Results

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. There are three important elements to observe about this plot. First, the curve has zero hysteresis; it follows the same curve when frequency is increasing as when frequency is decreasing. Second, the control system achieves zero steady-state-error when tracking a change in frequency. Lastly, a zero overshoot is observed when the frequency stops changing and only a small overshoot when the system saturates at maximum output or input. These are important properties for a system regulating frequency on a microgrid. It would be important for installation that either control over SOC is managed internally or managed by a central controller. An uncontrolled system like this would saturate at either full or empty and would only be able to supply regulation in one direction until reconditioned to 50% SOC.

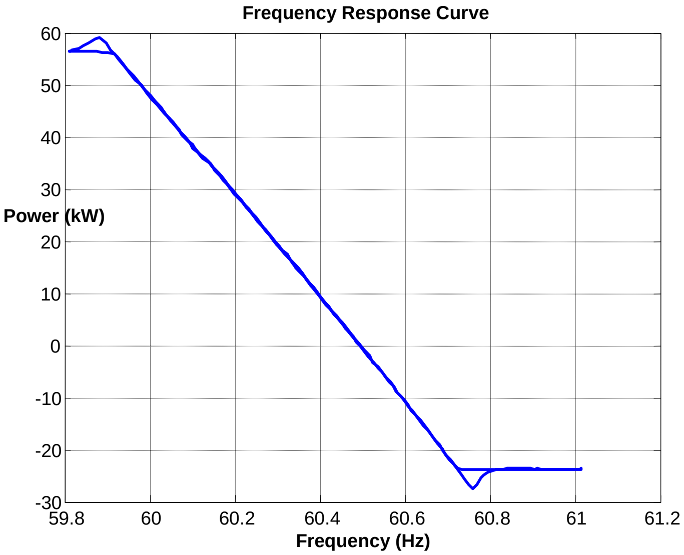

Figure 6 Power/Frequency Curve

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 - a value provided by the manufacturer. A $480V_{LL}$ 3-phase utility grid simulator is 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 decreases the magnitude of the voltage down to 0.95 V_{LL} at 60Hz. Sandia records 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.

3.4.1 Voltage Response Test Results

The system did not have voltage support capability at the time of testing so no data is available. Since the system is able to control reactive power and able to measure voltage, system programming change could enable this function.

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 0^{th} 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

Figure 7 shows the measured THD and power conversion efficiency at each step. Note that the Princeton Power system includes a 100kVA, 480V delta / 208V Y, dry-type transformer which is included in these efficiency measurements. As the inverter is rated at 100kW and the range of this testing is at and below 60kW, it is not being operated in its optimal configuration. Even still the system has max conversion efficiency in excess of 94% including the additional losses already stated. At the highest tested output the systems THD was 9.8%.

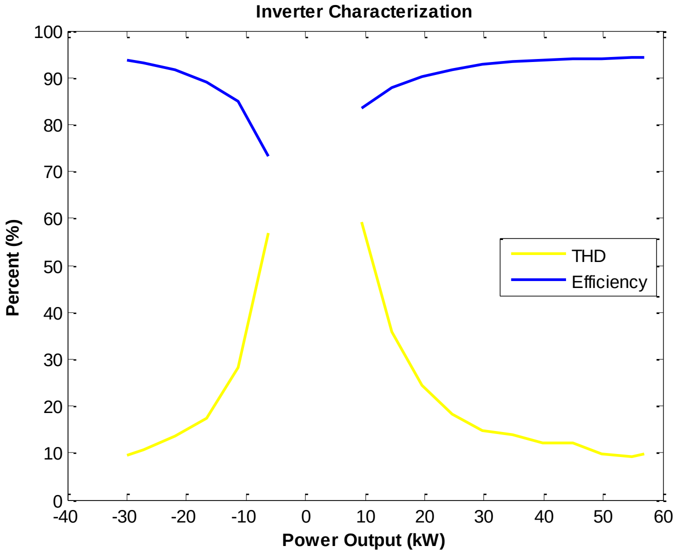

Figure 7 THD and Power Conversion Efficiency Test Results

4. ANALYSIS AND CONCLUSIONS

4.1 Performance

The data in Figure 2 show that the system has an energy performance of 64.7 kWh and a round trip efficiency of 78.7%. 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 during which the error between the response and the steady-state value falls below 2% of the steady-state value. Overshoot Percentage is the percent that the peak value of the response exceeds the steady state value.

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

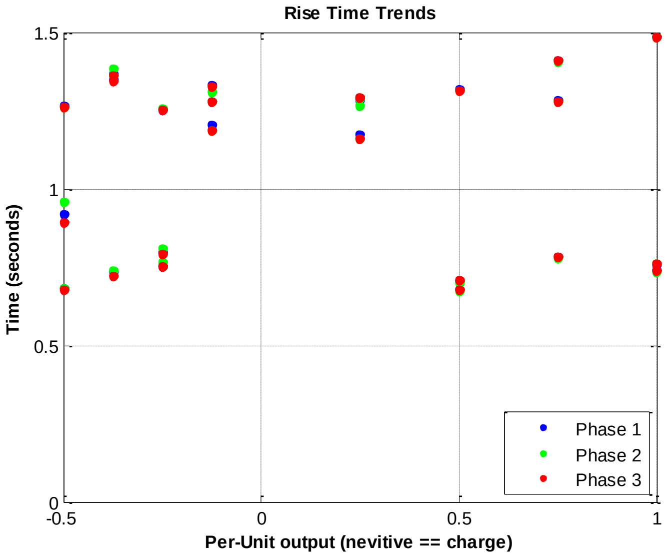

Figure 8 Rise Time

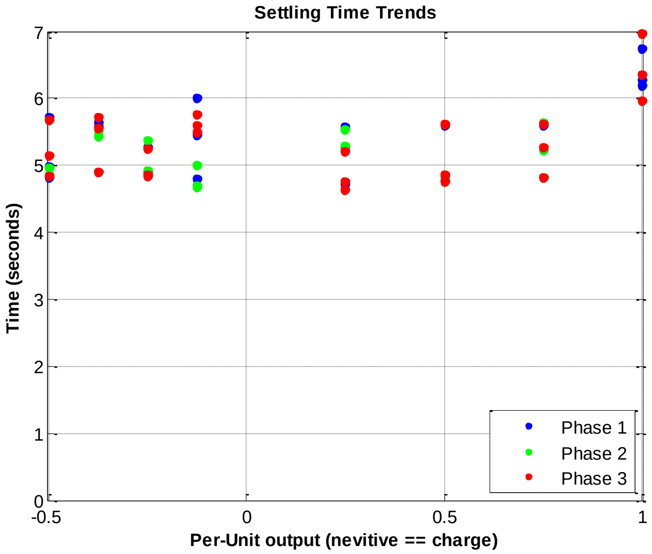

Figure 9 Settling Time

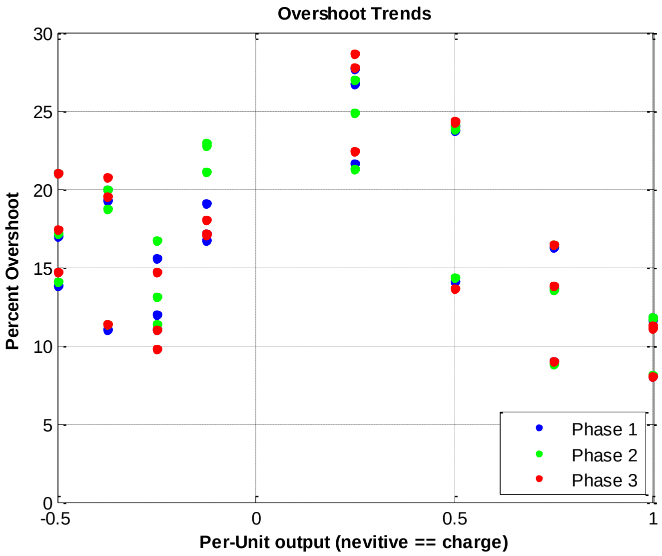

Figure 10 Percent Overshoot

This system behaved very consistently. It has a rise time of approximately 1 second. One second is the sample rate for the data acquisition. The results cannot be reported more precisely than this. The settling time was between 4.5 and 6 seconds with a 1 second longer time (7 seconds) at maximum power discharge. The overshoot was generally between 10% and 30% and was lower with higher power commands on charge and discharge.

4.2. Overall Assessment and Recommendations

The system has a very high performance design. The Li-ion batteries combined with a fast responding inverter yielded high capacity, efficiency, and controllability. Along with this performance comes less desirable consequences such as high Total Harmonic Distortion (THD), and high overshoot on commanded power set points. As this is a prototype these issues can be addressed in future designs and precise requirements for the response can be designed to, to meet the needs of a given microgrid.

This prototype system had a very involved setup. The Li-Ion batteries had to be shipped separately from the system and had to be installed onsite. This procedure, which did not include startup and commissioning, required a full work day of three people (2 workers and 1 safety watch) to complete. To make setup go more smoothly, the addition of module covers, pre-installed, keyed inter-module connectors and lifting handles/straps is recommended.

During takedown of the battery, it was observed that the Li-Ion Battery module on the end of the bottom row had expanded to the point that it burst two out of four of the metal straps that hold the individual cells together in a module. After the modules could be removed it was observed that every module on the bottom row (6/20) had burst at least one metal strap and that one (Module # 2) had burst all four straps. The minimum cell temperature was checked before each charge and the value never was below 10C (manufacturer minimum charge temperature is 0C). One possible cause is that the temperature differential from the top rack to the bottom rack may have caused a difference in internal impedance, resulting in increased expansion during charge. Being stored in cold conditions overnight and being tested at high altitude might have contributed to this. Another factor that may have contributed is that the batteries used in this system were reused from previous applications.

The system's ability to save fuel in a FOB microgrid has yet to be assessed. Its high efficiency and discharge power ability could be advantages while its low charge power ability could be a disadvantage. Other factors in implementation include its very fast response rate, its high harmonic distortion, and the lack of safety in design and operation. As this is a prototype unit these issues can 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.

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