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# Test Report: Milspray Scorpion Energy Storage Device

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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 have supplied their systems to SNL Energy Storage Test Pad (ESTP) for functional testing and a subset of these systems were selected for performance evaluation at the BCIL. The technologies tested were electro-chemical energy storage systems comprised of lead acid, lithium-ion or zinc-bromide. MILSPRAY Military Technologies has developed an energy storage system that utilizes lead acid batteries to save fuel on a military microgrid. This report contains the testing results and some limited assessment of the Milspray Scorpion Energy Storage Device.

# ACKNOWLEDGMENTS

This work was funded by the Department of Energy Office of Electricity Delivery and Energy Reliability.

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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 |
| 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, command 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. Milspray provided Sandia their Scorpion Energy Storage System for testing; the results of which are documented in this report.

# 2. TECHNOLOGY DESCRIPTION

Milspray Scorpion energy storage system utilizes a valve-regulated lead acid battery bank with a rating of 15kW and 79kWh. The installed inverter in the system is composed of three single phase inverters, each rated at 120Vac and 6kW. The inverters are limited to 5kW to prevent overtaxing the installed lead acid batteries and to maintain design life. The entire system is capable of fitting inside a tricon container but as of now resides in two quadcon containers. The primary container holds the inverters, controls and some of the batteries while the secondary container holds additional batteries and has racks that can hold a photovoltaic array. This system also has inputs for photovoltaic 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 January of 2013.

**Figure 1 Milspray 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 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 ambient temperature of the enclosure is monitored by a thermostat that controls a pair of fans to vent the hot air and pull cooler air in from the outside. While this lessens the likelihood of thermal runaway, it neither detects nor reacts to it. 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.

Hydrogen becomes combustible at approximately 4% concentration in air. As long as the internal air is vented regularly it becomes unlikely for the system to be able to reach this concentration. However in cold conditions, where the fans are rarely if ever in operation, and the system is left closed for an extended period of operation, it may be possible to generate enough hydrogen to reach these levels. The maintenance schedule should include venting the internal air during operation often enough to prevent the buildup of hydrogen.

### *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. There were no exposed conductors in either enclosure to prevent shock. The system was tested well-grounded (less than 1 Ohm from system ground to ground rod lug) to prevent static buildup. The battery bus was held at 48V DC which is below the accepted safe working voltage in most applications. Additionally, this reduces the ark flash potential to minimal levels when working on the equipment. The AC external connections were interlocked to the output of the inverters which is a design that is conducive to Lock-Out-Tag-Out (LOTO) safe work practices. Because of these mitigating factors, the system had a minimal level of electrical hazard given the technology.

### *2.1.3 Chemical Safety*

VRLA have an acidic gel electrolyte that can be hazardous if the container is ruptured. The Materials Safety Data Sheet (MSDS) should be consulted if damage is observed that exposes an operator to the gel electrolyte.

### *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 Milspray Scorpion 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. Many battery systems limit their usable SOC range to prolong design life; therefore 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 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 79 kWh installed VRLA lead acid batteries. By limiting the voltage operating range, the system operates from 50%-90% SOC (recommended by Milspray); the rated system capacity is reduced to 32kWh. To validate this rating and to determine efficiency and standby losses, the system was fully charged and then a 15kW power command was sent to the energy storage system to discharge 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. Note that DC measurement was not practical on this system and hence Amp-hours were not recorded. The same 15kW power command was repeated four times. The power output profile in Figure 2 was selected as a representative sample. Phases 1, 2, and 3 respond to the 15kW power command (5kW per phase) and held that value until the low voltage limit on the battery was reached. Because of slight differences in this measurement, the inverters reached this limit at different times. This causes the inverters to drop off one at a time to maintain a DC bus voltage within the energy storage system limits.

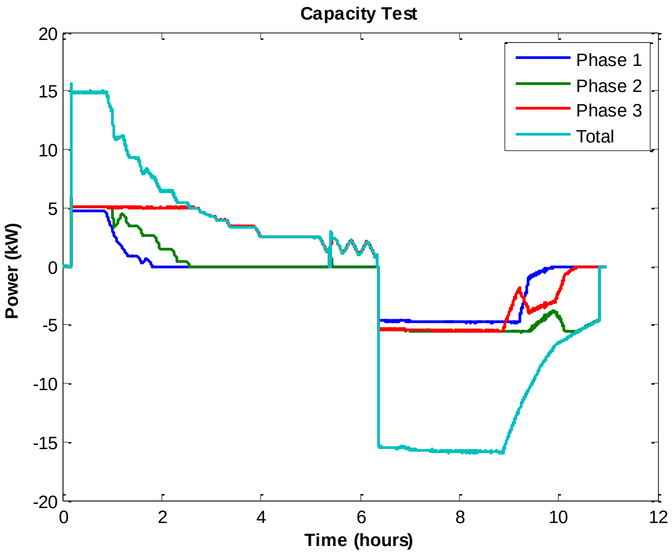

**Figure 2 Rated Power Capacity Test**

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

**Table 1 Capacity Test Results**

| | |
|---|---|
| Energy Discharged | = 34.9 kWh |
| Energy Charged | = 56.4 kWh |
| Max Power, Energy Efficiency | = 62.0 % |
| Standby losses* | = 38.0 W |

*Recorded during rest periods between tests

## 3.2 Command Response Test

Command Response testing is 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). The data is recorded from 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 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.

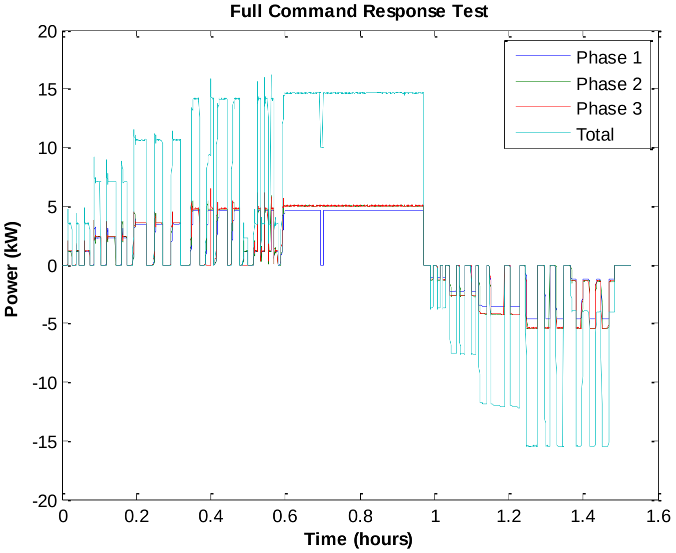

**Figure 3 Command Response Test Results**

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.

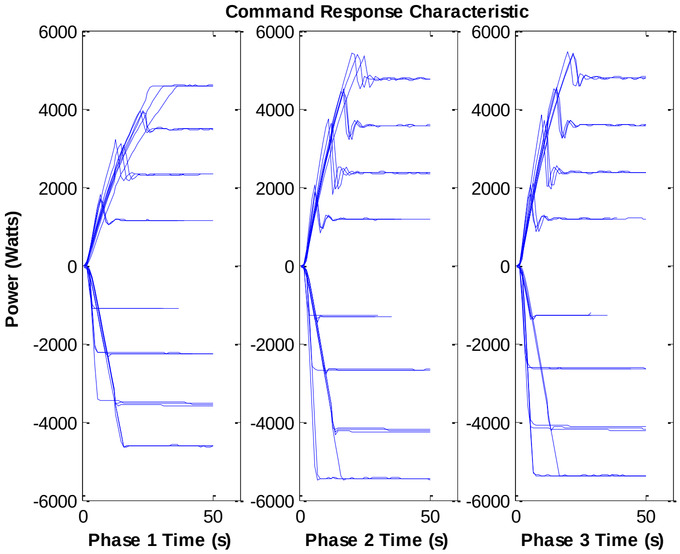

**Figure 4 Per-Phase System Step Responses**

## 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 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 480$V_{LL}$ 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 be 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).

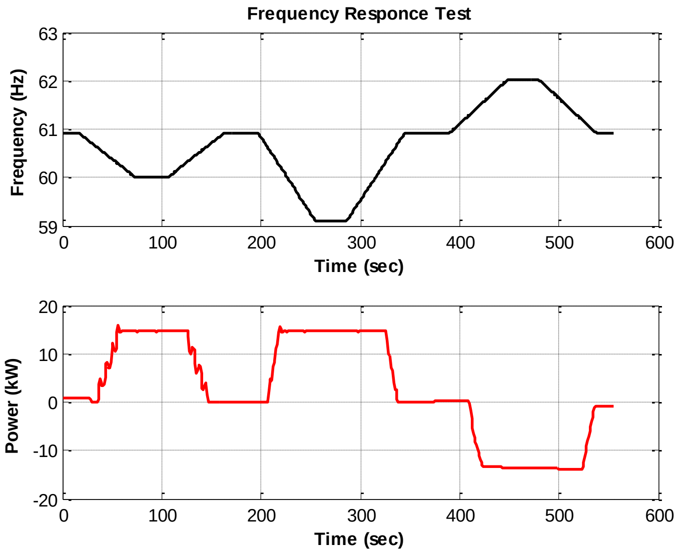

**Figure 5 Frequency Response Test Results**

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. Observe that there are four levels of discharge where the system plateaus as the frequency falls. When the frequency is falling slowly during the first ramp, the system has time to overshoot and settle before being commanded to the next plateau. When the frequency is changing more quickly in the second pulse, the system responds more smoothly (only because it does not have time to settle before being commanded to the next plateau). When the frequency increases significantly, the system responds by charging at full rate. There is hysteresis in this plot because it takes time for the system to ramp up to full charge and ramp down to rest.

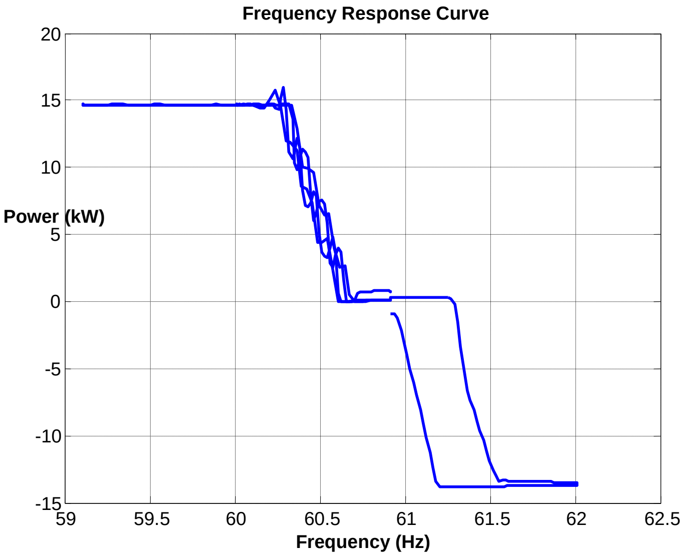

**Figure 6 Power/Frequency Curve**

These curves demonstrate the system's ability to respond to changes in frequency. Again the specific shape of the response could be changed to suit the needs of a given microgrid. While the low resolution of this response may be inadequate for certain applications, it may work well enough for others. The requirements of a specific microgrid would determine if the six plateaus between full charge and full discharge are acceptable.

## 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 218$V_{LL}$ down to 0.95pu or 198$V_{LL}$. SOC does not matter for this test because reactive power should not push or pull real power from the batteries. A 480$V_{LL}$ 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 with the utility grid simulator returning the voltage magnitude back to the starting point of 1.0pu $V_{LL}$.

### *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.

### *3.5.1 Inverter Characterization Test Results*

Figure 7 shows the measured THD Percentage over the full range of operation. At full discharge the system is just under 5% THD, and at full charge the system is just over 5%THD. Note that the actual noise imposed on the connected power system is the

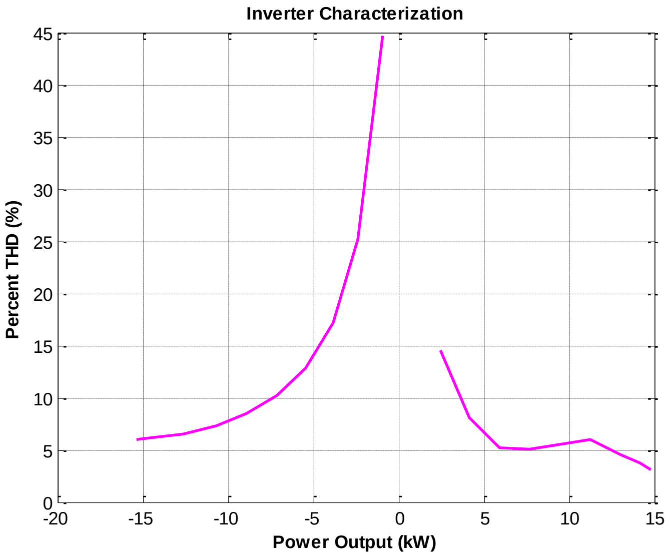

**Figure 7 THD Power Quality over Operational Range**

Note that actual off-frequency line distortion is a function of THD multiplied by output power level. Hence even high THD at low power can result in less harmonic noise injected into the power system (as it does in this case).

# 4. ANALYSIS AND CONCLUSIONS

## 4.1 Performance

The data in Figure 2 shows that the system has an energy performance of 34kWh and a round trip efficiency of 62%. This is a combined DC/AC efficiency since it includes the DC to AC conversion during discharge, the AC to DC conversion during charge, the systems standby losses, and the 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 8, 9, and 10 show the measured trends of the Rise Time, Settling Time, and Overshoot Percentage calculated from the responses in Figure 4.

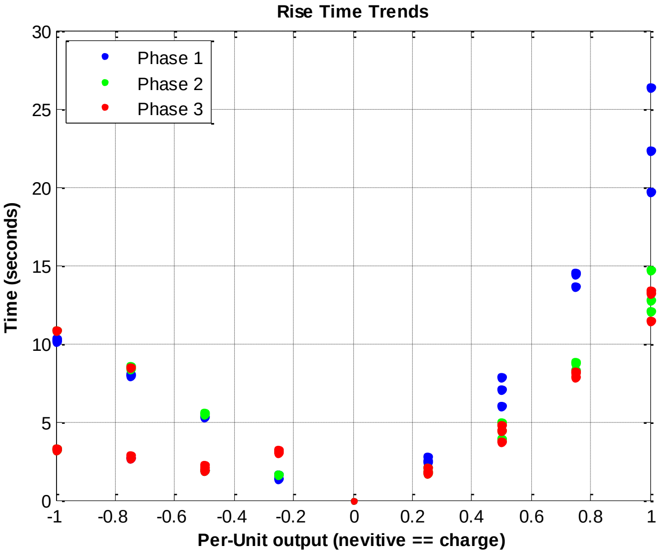

Figure 8 Rise Time

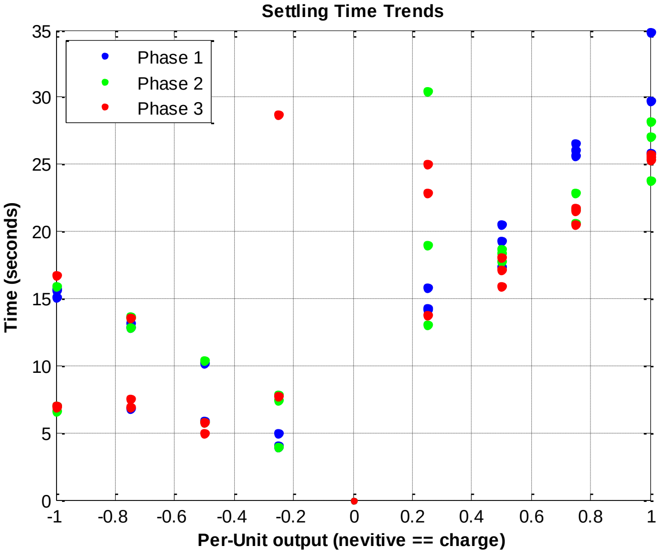

Figure 9 Settling Time

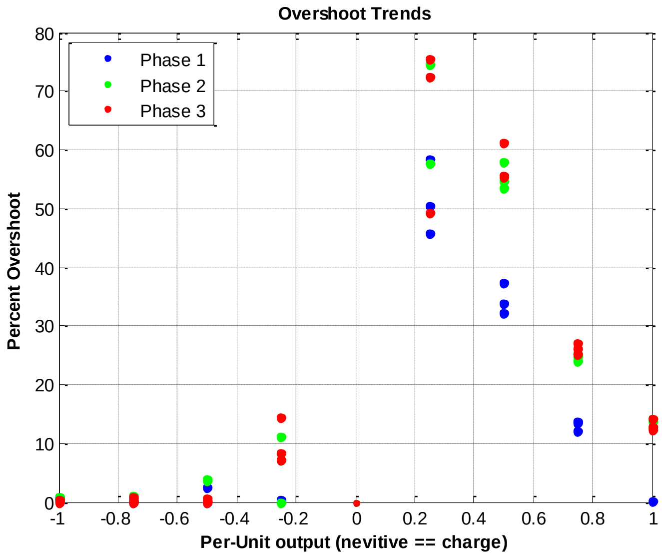

**Figure 10 Percent Overshoot**

With the exception of a few outliers, the phases follow some general trends. In rise time, the devices are consistent on discharge, but the inverters had two distinct ramp rate limits, on charge. Each phase used both of these ramp rates during testing with no discernible cause. The settling time varied more on discharge (especially at low power) than on charge, where it followed two distinct trends. This stems from the two trends observed in the rise time. Each phase had less Percent Overshoot (%OS) with higher power levels on both charge and discharge. The %OS is much less for phase one than for phases 2 or 3, even though it is following the same set point. This is likely due to an internal setting that limits the maximum ramp rate.

## 4.2 Overall Assessment and Recommendations

The system was very simple to set up, merely requiring interconnection of containers to prepare for operation (a step that would not be required in the future, single tricon design). It was controlled either locally or remotely using the inverter manufacture's basic hardware and software. This was functional for the purposes of testing and integrating the system with a future master controller should be possible.

Three single-phase inverters are used instead of one three-phase inverter which has both advantages and disadvantages. Using the three single-phase inverter allows for each phase to respond to a power command independent of the others. This would be desirable for systems that are very unbalanced between the phases because each inverter can respond to the phase that it is attached to without having to determine the phase imbalance. Three phase inverters, just like generators, cannot operate on very unbalanced systems (greater than 20% unbalance). This is a problem that three independent inverters would not encounter.

As shown in the capacity test, the inverters shut off one phase at a time to maintain a DC voltage limit. This allows for the system to continue to operate (at lower power) even after the low DC voltage limit has been reached. However, since only one phase is turned off, this can cause additional unbalance of the three phase load if the inverter that shuts off corresponds to the phase that is more heavily loaded. In the case of a lightly loaded microgrid, this unbalancing can cause the generators to trip if the difference in the phases is more than what the generators are rated for. Because this is only controlled by the DC bus voltage, it could potentially add to system imbalance. A master controller would be able to control the individual inverters to actually correct some phase imbalance in a microgrid.

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 easily 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, automating the ventilation fans to cycle the internal air occasionally (even in cold environments to prevent hydrogen buildup), and temperature measurement of the batteries to detect and prevent thermal runaway.

The system’s ability to save fuel in an FOB microgrid has yet to be assessed. Its low cost design will make it less expensive to deploy and its low standby losses will make it less impactful during periods of inactivity. Other factors of implementation include its safety in design and operation, inconsistent response rate, and per phase control capability. Further analysis, testing, and demonstrations are necessary to determine the effect of these factors on fuel savings and the potential for overall installation success.

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