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PERFORMANCE ANALYSIS OF SODIUM SULFUR BATTERY IN ENERGY STORAGE AND POWER QUALITY APPLICATIONS

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ABSTRACT: *This paper presents the evaluation of the sodium-sulfur battery technology in energy storage and power quality applications. The evaluation of this technology in the USA was first performed at the Dolan Technology Center of American Electric Power, Columbus, Ohio. In the first phase of the research, extensive testing and analyses were performed on a sample module to understand the internal characteristics and dynamics of the battery, and then performance drivers were defined. A demonstration project that combines nominal rating of 500kW for 30 seconds of power quality mitigation and up to 750kWh of peak shaving capacity at a maximum power of 100kW was installed in September 2003 at one of AEP's Office Buildings in Gahanna, Ohio. Evaluation so far has shown that the sodium sulfur batteries can solve variety of power quality problems and provide economical energy storage for a wide range of power system and energy management applications. AEP and the project partners are continuing to monitor and evaluate the system.*
KEYWORDS: *Sodium Sulfur battery, energy storage, peak shaving, power quality.*

SODYUM-SÜLFÜR BATARYALARIN ENERJİ DEPOLAMA VE GÜÇ KALİTESİ UYGULAMALARINDAKİ PERFORMANS ANALİZİ

ÖZET: *Bu makale sodium sülfür bataryalarının enerji depolama ve güç kalitesi uygulamalarındaki performanslarını değerlendirmektedir. Bu yeni teknolojinin teknik değerlendirmesini Amerika'da ilk olarak Dolan Technology Center of American Electric Power, Columbus, Ohio, araştırma grubu gerçekleştirmiştir. Araştırmanın ilk safhasında, bu ileri batarya sisteminin iç karakteristiklerini ve dinamiklerini tanıyıp anlamak ve daha sonrada performans parametrelerini belirlemek üzere test ve analizler yapılmıştır. Sodyum sülfür bataryalarının, 30 saniye süreli 500 kW'a kadar güç kalitesini iyileştirme ve 100 kW'da 720 kWh'lik enerji kapasiteli tepe kırpma yeteneklerinin birleştirildiği bir dizaynı test etmek üzere yeni bir sistem Eylül 2003'te AEP'a ait bir ofis binası için kurulmuştur. Şu ana kadarki testlerden elde edilen sonuçlar, sodyum sülfür bataryalarının geniş bir yelpazedeki güç kalitesi problemlerini çözdüğünü ve enerji yönetimi uygulamalarında ekonomik bir alternatif teknoloji olduğunu göstermiştir. Sistemin izlenmesi ve değerlendirilmesi sürmektedir.*
ANAHTAR KELİMELER: *Sodyum sülfür batarya, enerji depolama, tepe kırpma, güç kalitesi.*

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I. INTRODUCTION

Electrical energy is a rare example of a product that without energy storage must be consumed at the instant it is generated. This inability to economically store the energy in meaningful quantity adds complexity to the energy delivery and is a contributing factor to price level and volatility and power quality related problems. Therefore, it is necessary to build and operate the power system to meet peak demand, adding significantly to the cost of service. For this reason, electrical energy providers have been looking for large-scale economic storage of electrical energy. Energy Storage can be used to provide various combinations of the following applications [2], [8-9]:

- Peak shaving/Load leveling
- Improved power quality
- Emergency/Backup energy
- Improved operating condition
- Voltage support
- Spinning reserve
- Loss reduction
- Defer new central generation
- Improved utility system reliability
- Deferments of new or upgraded T&D infrastructure
- Low cost energy

The value of energy storage is substantial and is expected to grow to meet industry operational challenges and as the cost of power interruption increases. One high value storage application is for load leveling, or peak shaving (PS), which is accomplished by using existing generation, transmission and distribution assets to charge storage devices when load is low and discharge them during heavily loaded periods. Figure 1 illustrates a typical load leveling cycle over a 24-hour period. This process enables efficient operation of generation facilities and maximizes T&D infrastructure utilization. In addition, the charge/discharge cycle allows the energy storage operator to purchase low cost energy to charge the battery during off peak hours and sell that energy during peak periods when the price of electricity is high [8].

Significant worldwide research has resulted in the development of energy storage technologies that are well suited for high power and high-energy applications. Technologies developed for high power applications include batteries, capacitors, flywheels and super conducting magnetic energy storage devices, which are typically associated with power quality solution and short time duration applications. High-energy applications include load leveling and peak shaving.

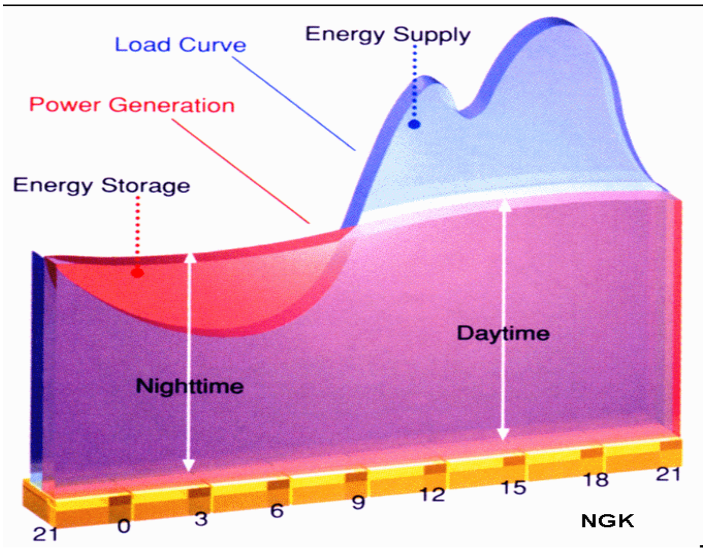

Figure 1. Load leveling cycle [4].

II. SODIUM SULFUR (NAS) BATTERY

II.1 The Basic Operational Principles of the NAS Battery

The diagram in Figure 2 illustrates the electrochemical reaction inside a NAS battery. A NAS battery consists of sulfur at the positive electrode, sodium at the negative electrode as the active materials, and the Beta alumina of sodium ion conductive ceramic that separates both electrodes [4].

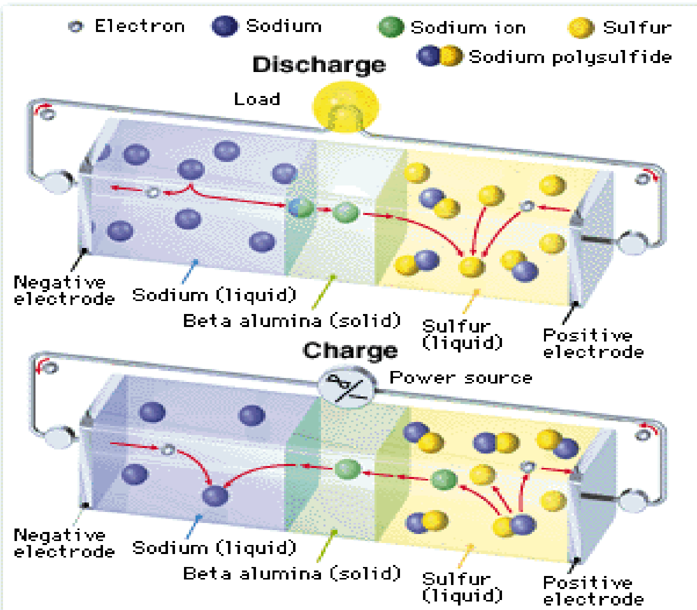

Figure 2. A simple diagram that shows the electrochemical reactions inside a NAS battery [4].

NAS battery, which needs to be hermetically sealed for safety, is kept at approximately 300°C and is operated under the condition that the active materials at both electrodes are liquid and its electrolyte is solid. NAS battery presents its optimum internal characteristics and provides excellent performance at this temperature since both of the active materials react smoothly and the internal resistance becomes low. Moreover, Due to reversible charging and discharging capability, NAS batteries can be used continuously.

Approximately 2V is generated between the positive and the negative electrodes at about 300°C. When a load is connected to the terminals of NAS battery, electric power is supplied to the load. During discharge, the sodium ions in the negative electrode migrate through the solid electrolyte to the positive electrode, while the electrons move from the negative electrode through the external circuit to the positive electrode as shown in Figure 2. An electric current is generated by the flow of electrons in the external circuit.

With the progress of discharge action, sodium in negative electrode decreases by the consumption, but at the same time, sodium polysulfide is formed in positive electrode. During charging, electric power that is supplied by an external source causes to form sodium in the negative electrode and sulfur in the positive electrode by following the reverse process of the discharge. Because of this reversible electrochemical reaction, the energy is stored in the battery [4].

II.2 NAS Battery Attributes

NAS Battery systems provide unique solutions to energy management (peak shaving), reliability (outage) and power quality (momentary interruption) issues. These applications increase asset utilization, provide alternatives to meet peak demand and improve quality of service. This technology can be used to deliver high quality service in a complex market. The NAS battery technology demonstrates the following attributes [6-9]:

- **High energy density:** Up to 3 times lead acid battery, enabling efficient space utilization
- **High efficiency:** Up to 89% cell dc efficiency with no self-discharge
- **Long cycle and shelf life:** More than 2500 full charge and discharge cycles, up to 15 years
- **Peak pulse power capability:** Up to 5 times the nominal rating [13].

These attributes make NAS technology well suited for combined peak shaving and power quality applications. Combined peak shaving (PS) and power quality applications are of particular interest in the U.S. market. Power Quality (PQ) solution requires the injection of power for short time durations to mitigate power disturbances such as voltage sags and momentary outages and, if required, to transition to backup generation. For example, power pulses of 30 seconds are sufficient to address more than 95% of power quality events and provide transition to standby engine-generator sets. These applications exploit the NAS battery's capability to instantaneously deliver pulses of power at several times the nominal rated power [7-10].

The NAS battery can also be used in UPS applications where its high energy density gives it a significant size advantage over other batteries. PQ operation is available during all modes of operation including, standby, charging and discharging.

III. DESCRIPTION OF THE DEMONSTRATION PROJECT

The partners of American Electric Power (AEP) in this project include NGK Insulators, Ltd. (NGK), Tokyo Electric Power Company (TEPCO), ABB Inc. of New Berlin, Wisconsin (ABB), the U.S. Department of Energy/Sandia National Laboratories and EPRI [5]. A simplified one-line diagram of the system installed in Gahanna, Ohio at one of AEP's office buildings is shown in Figure 3. The NAS battery system consists of NAS battery modules and controller, power conversion system (PCS), necessary enclosures and external switchgear to safely interface the PQ/PS system to the utility power grid. The following sections describe the system components in more detail.

III.1 NAS Battery Modules

The system uses two NAS battery modules. One module alone provides 375kWh of peak shaving capacity at a maximum power of 50kW for 2500 full charge/discharge cycles. The NAS batteries are manufactured and supplied by NGK insulators, Ltd. in Japan [4].

The NAS batteries also have the capability to provide 5 times the rated power, 250kW, for a short time, typically up to 30 seconds. The duration of peak power is limited by the internal temperature rise of the battery [10-12].

With cooperative efforts, NGK, TEPCO and AEP have developed various discharge profiles that successfully combine the peak shaving and power quality applications. The choice of profile for an application is made based on the desired level of PQ protection, peak shaving energy, and the desired lifetime of the batteries. As an example, an application that requires PQ mitigation up to 30 seconds at 500kW level should reduce peak shaving energy to 158kWh in a combined operation if 2500 full charge/discharge cycles are desired. A package of various profiles for a wide range of applications is loaded into the system memory, where they can be selected easily through the user interface.

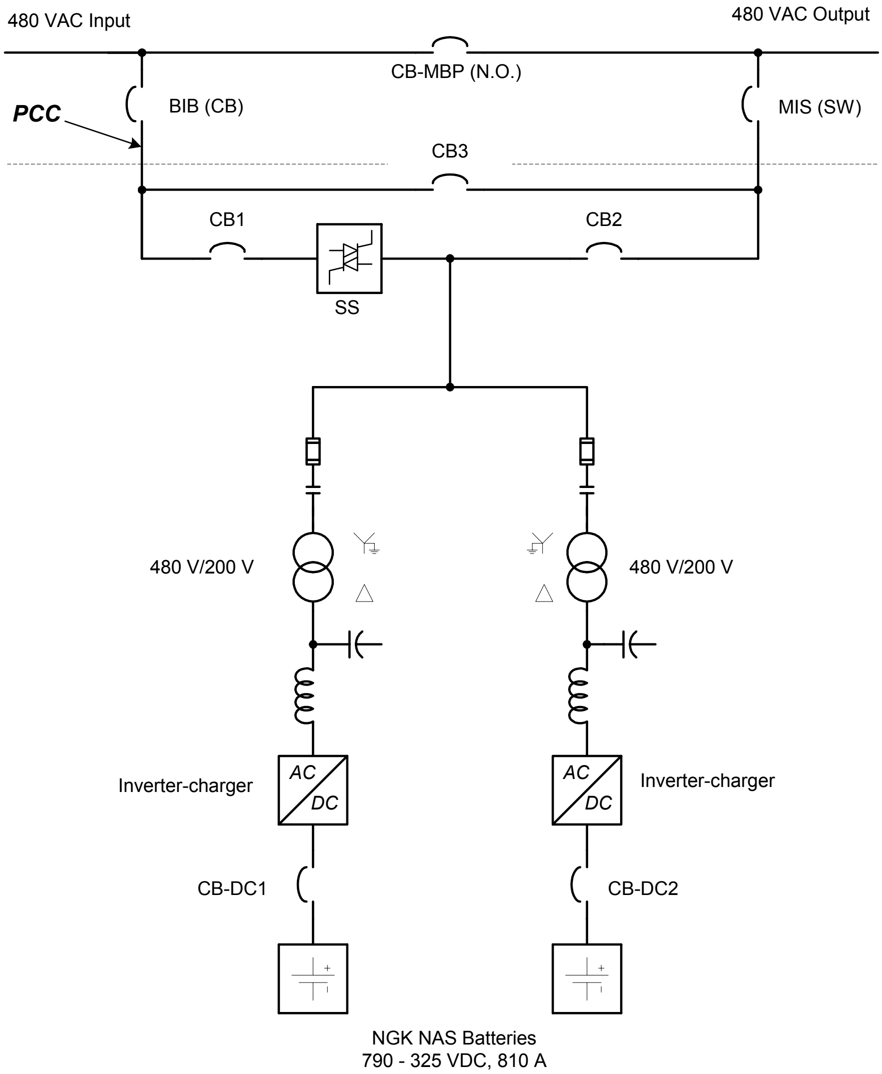

Figure 3. One line diagram of the implemented multi-function NAS battery energy storage system.

NAS batteries must be maintained at an elevated temperature at all times to accomplish energy storage function as described in section II.1 [1-4]. External heaters located at the bottom and the sides of the battery modules are used to keep the cell temperatures at the desired level as needed. The nominal temperature of the implemented system is maintained at 325 ˚C to successfully achieve combined operation, peak shaving with 500kW PQ mitigation. External circuitry with controllers maintains the electric power for the heaters.

The nominal operating voltage of the batteries is 700Vdc. Terminal voltage varies between 325V and 790V. The dc bus voltage drops to 325V when the system is at maximum load and goes up to 790V during charging. Each module has current rating up to 810Adc.

CB-DC1 and CB-DC2, shown in Figure 3, are 1000V and 1000A dc breakers. They are operated by either battery module controllers or the PCS controllers. Abnormalities internal to the battery modules, such as cell failure, over current, abnormally low cell voltages, extreme temperatures, etc., which are monitored by the battery controllers, can trip the dc breakers to protect the batteries from failure. Similarly, some specific abnormalities detected by the PCS monitoring system can trip the dc breakers to protect the power electronics and rest of the system.

III.2 Power Conversion System (PCS)

The PCS uses two bi-directional converters to process energy in each direction and uses PWM technique to regulate a voltage or a current depending on the operating mode.

The LC filters placed at the output of each converter are used to eliminate the high switching frequency noise and unwanted harmonics from going into the power system lines. The output of the LC filter, as shown in Figure 3, goes into a step-up transformer.

The transformers provide the following functions: a galvanic isolation between the power grid and the power electronics; a delta-wye transformation since the source side of the system is grounded wye 5 wire system; and the regulation of 480Vac at the grid side of the system. In this application, the transformer is made with high leakage inductance to further improve the filtering efficiency of the LC filters.

An SCR based static switch (SS), which is surrounded by appropriate circuit breakers that provide different operational schemes, is used to achieve fast transfer of the sources during a PQ event. The static switch is designed to provide transfer times less than a quarter cycle. The circuit breaker CB3 is used to provide bypassing of the NAS battery system for maintenance or when a NAS battery system problem is detected.

IV. SYSTEM OPERATIONAL MODES

Figure 4 represents the simplified model of the system shown in Figure 3. When the grid is healthy, the NAS energy storage system operates as a peak shaving device, as shown on the left in Figure 4. Correspondingly, when the grid is gone or out of tolerance, the system operates as a PQ device (or a UPS), which is the model shown on the right in Figure 4.

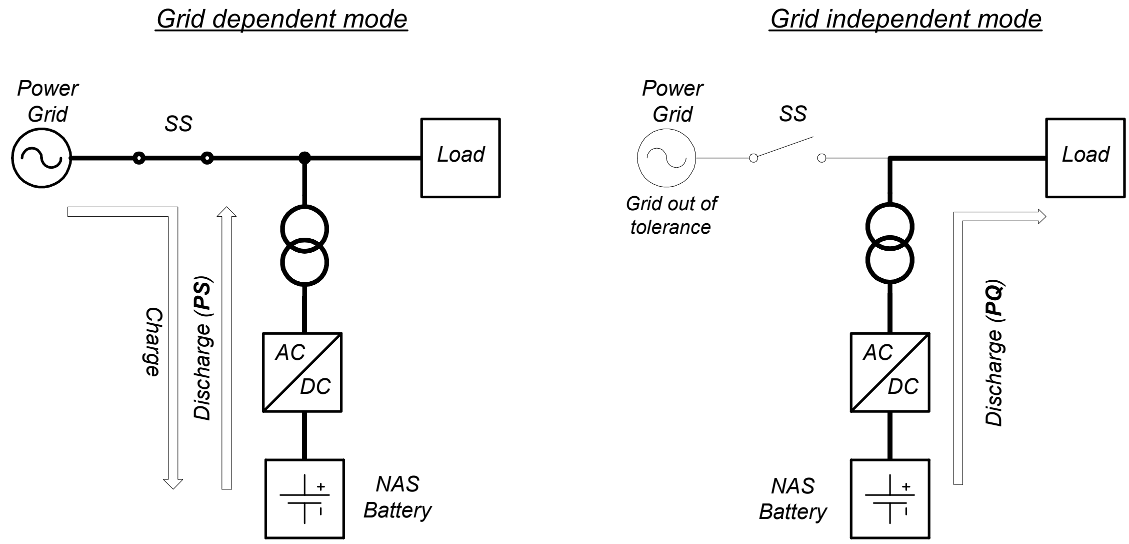

Figure 4. Simplified version of the NAS battery system shown in Figure 3 [6].

When the system is in the PS mode, it goes through four different operational states. Operation of the system in these four states, which are briefly discussed in the following sections, can be characterized as a grid dependent mode since the static switch is closed, placing the power conversion system in parallel with the electric power system (EPS). For the same reason, the operation in PQ mode can be characterized as grid independent mode because the static switch is open and PCS is disconnected from the grid.

IV.1 Grid Dependent Mode

Charging State: In this mode, the grid supplies energy to the load and to the NAS batteries. Charging of the system is started during off-peak hours, typically during night time hours when the demand is reduced, and completed before the next high demand period, usually early in the morning.

Discharging State (PS): During peak shaving (or load leveling) operation, the system is in discharging state. The system is designed to peak shave on a daily basis excluding the weekends when the demand for electricity is reduced. Start and finish times of the daily discharge as well as the charge is settable locally from the human-machine interface (HMI) or remotely over the Internet. The PCS in PS mode becomes a voltage follower and operates as a constant power source inverter. The parameter that controls the power level during peak shaving is available to the user through the HMI so that the user can match the PS power with the load demand.

Standby State: The system has two standby states; one is between the charge end and the start of PS, second one is between the PS end and the charge start. During these states, the static switch remains closed and the gate pulses to the IGBTs in the ac/dc converter are blocked, energy only flows from grid to load but not from the batteries.

IV.2 Grid Independent Mode (PQ Mode)

When the grid monitoring system detects an outage or a grid out of tolerance condition, the static switch is turned off and the load is picked up by the NAS system. The advanced design of the NAS system achieves transitions in milliseconds enabling a continuous power flow to the load. Sags, swells, under frequency, over frequency and faults are some of the conditions that make the power grid out of tolerance. The PCS in PQ mode works as a voltage source inverter and regulates the output voltage such that it matches the grid voltage before the event. Since a target market of the NAS battery system is commercial and industrial loads that are considered critical, the specifications for this mode of operation should require compliance with the UPS standards.

V. TEST RESULTS AND PERFORMANCE ANALYSIS

V.1 The Test Results of Long Duration Activities (PS and Charge)

Figure 5 shows the operational pattern of the NAS battery system for one day testing. The system starts charging everyday at 8:00PM, which is considered the start of off-peak hours, and depending on the selected peak shaving profile, takes around 9 to 10 hours to complete full charging. The last one-hour of the charging cycle is the supplementary charging state. This special charging pattern, which is not quite visible due to slow sampling of the data, is performed to optimize the pulse power capability.

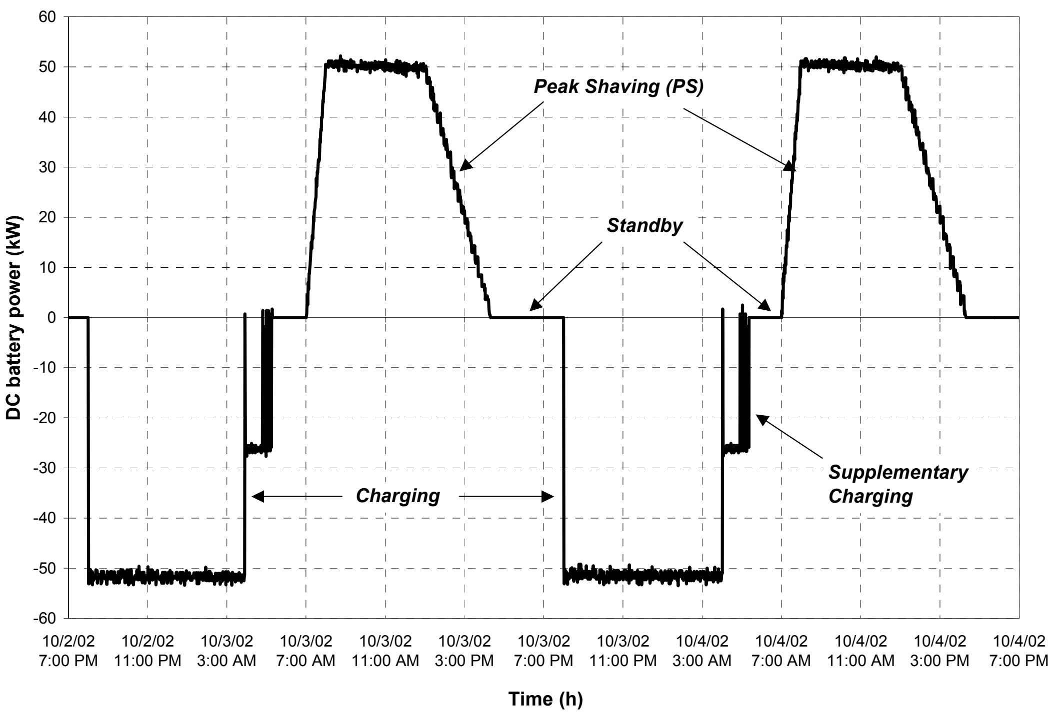

Figure 5. The operational pattern of the NAS battery system for one day of testing. The pattern includes peak shaving, charging, supplementary charging, and standbys.

After the charging is completed, the system waits in standby until the time set for the peak shaving action is reached. In the case shown in Figure 5, the peak shaving is started at 7:00AM in the morning, which is an average time when the high load demand is usually expected. The user can always reprogram the timing of these activities to match the load demands in different applications and installation sites. The PS profile shown in Figure 5 has one-hour ramp up, five hours flat and three hours ramp down regions and provides 375kWh of dc energy under normal operating conditions.

V.2 The Analysis of the NAS Battery Internal Characteristics

Figure 6 shows the dc power, current, and the terminal voltage of the NAS battery module during a daily discharge and charge cycle. Significant numbers of test were performed during the evaluation process to understand the internal characteristics of the NAS battery. The results concluded that the performance drivers of the NAS battery are internal resistance, internal temperature, open circuit voltage, and depth of discharge.

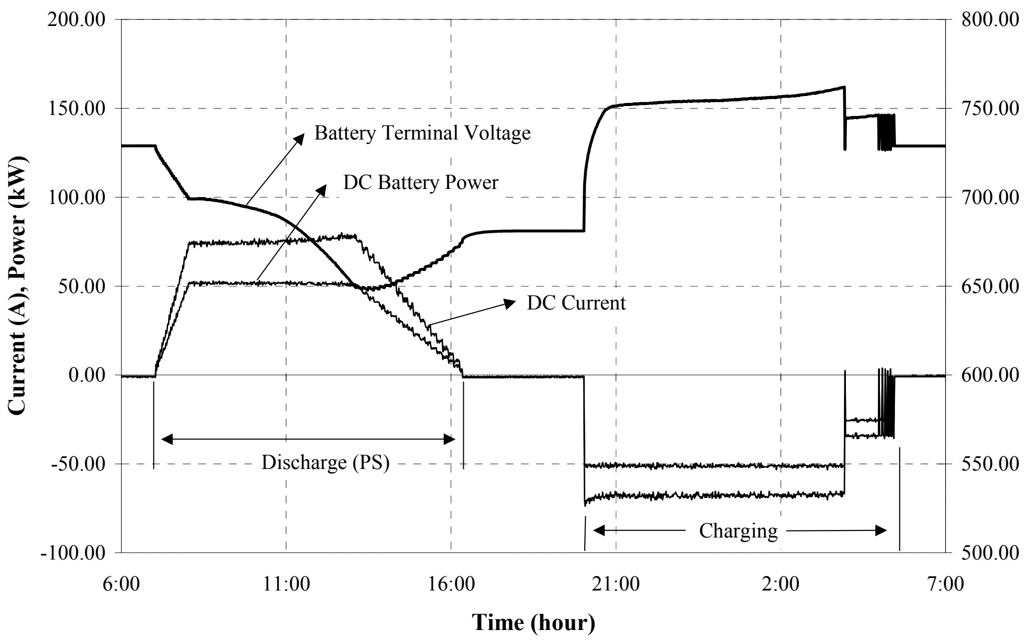

Figure 6. The dc power, current, and terminal voltage of the NAS battery module during a daily discharge and charge cycle.

Temperature is the most significant parameter that defines NAS PQ performance as it has a direct affect on the resistance. By controlling temperature, it is possible to obtain the necessary internal resistance required for PS or PQ operation. Figure 7 shows the temperature variation of the NAS battery module. Operating temperature of this module is set at 325°C. However as the battery discharges, the bottom temperature increases up to 350.50°C. The maximum safe operating temperature during a nominal peak shaving is 360°C. During a combined operation, the overall temperature rise caused by the PQ events should not go beyond 355°C, which is manufacturer's specification.

Test results have shown that the PQ capability of the battery improves at high temperatures. While the PQ readiness of the battery is achieved by keeping the temperature high, the maximum allowable temperature limits the PQ availability. Therefore, proper thermal management is needed for optimum performance.

Figure 8 shows the battery total internal resistance, open circuit voltage, dc power, and terminal voltage for the same module discussed earlier. Internal resistance consists of two components: ohmic and polarization resistances. Ohmic resistance consists of the beta alumina tube and other components and decreases with increasing temperature. Polarization resistance is a result of chemical states and varies with depth of discharge and temperature. Polarization increases as the depth of discharge increases up to some depth of discharge, which is characterized by a change in chemical state, and then gradually decreases [1], [10-11]. The ohmic resistance is measured as 0.4 Ohm, which is shown in Figure 8. The increase of the internal resistance from this value to approximately to 1 Ohm is due to the polarization effect. The polarization resistance causes more voltage drop during long term discharges. In response to this, an increase in the current is observed as shown in Figure 6. However, the effect of polarization during a short PQ pulse is negligible. The only component of the resistance to worry about during PQ discharges is the ohmic resistance.

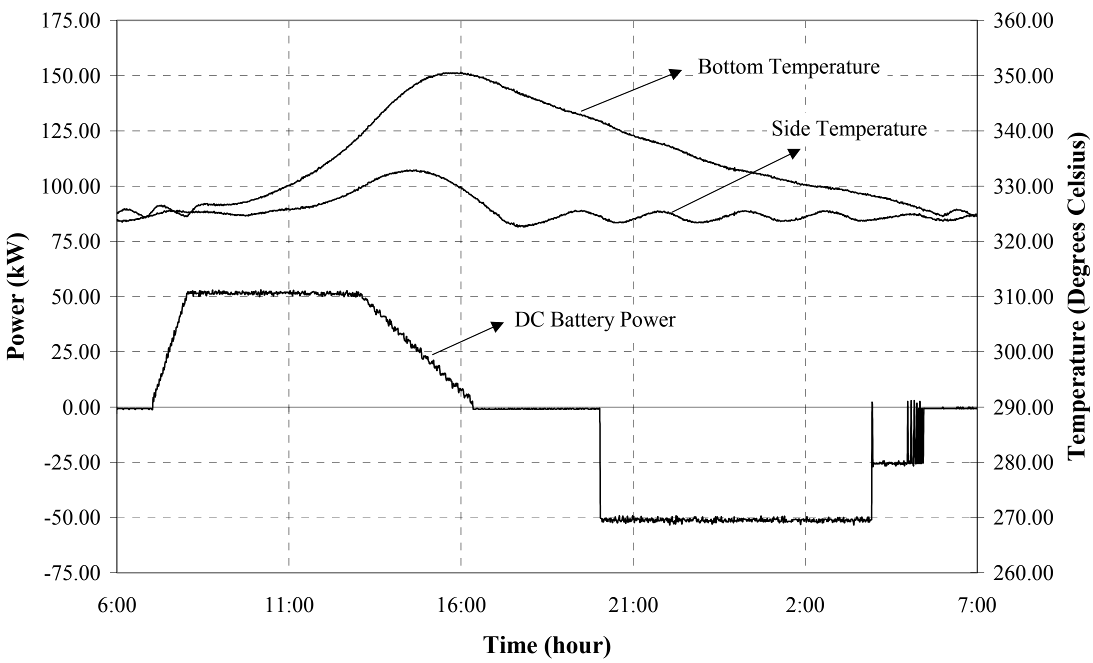

Figure 7. The dc power, side and bottom temperatures of the NAS battery module.

Another parameter that affects PQ performance is the open circuit voltage, which is dependent on the depth of discharge. Deep discharge of the battery causes a decrease in open circuit voltage that limits PQ capability. The analytically calculated open circuit voltage of the 50kW module is shown in Figure 8.

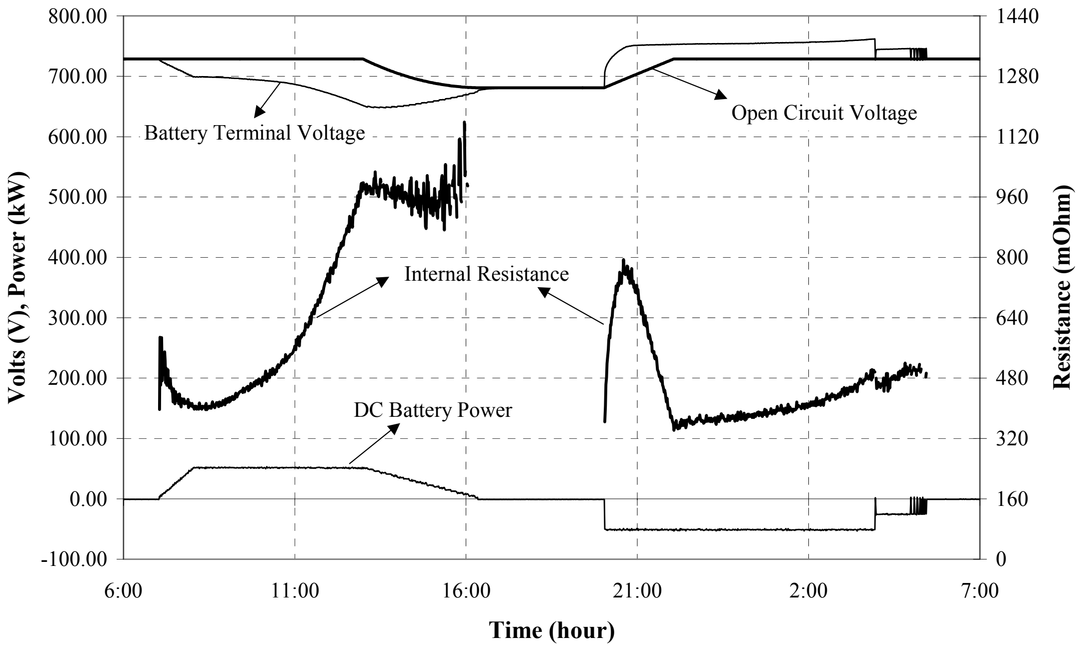

Figure 8. The battery total internal resistance, open circuit voltage, dc power, and the terminal voltage of the NAS battery module.

V.3 Results of Power Quality (PQ) Tests

Figure 9 shows the result of combined peak shaving with five times the nominal power for 30 seconds PQ protection test for battery module #1. Similar results were obtained for module #2 due to the parallel operation. Moreover, the test results measured at the ac side indicate a satisfactory operation. The system performs peak shaving at 100kW for six hours and successfully responds to six power quality events, supporting a 500kW load. The PQ events were initiated by opening a circuit breaker that was placed on one phase of the three-phase source. At the end of this combined operation, the battery (module #1) delivered 253kWh of dc energy to the system bus; 240kWh of that energy was delivered due to the peak shaving function and 13kWh is due to the PQ protection function. As seen from Figure 9, losses in PCS cause the system to draw a little more energy from the batteries than their nominal ratings.

The last three PQ tests shown in Figure 9 were performed during standby state after the discharge cycle was completed. The results verify the PQ performance capability of the NAS batteries in deep discharge regions.

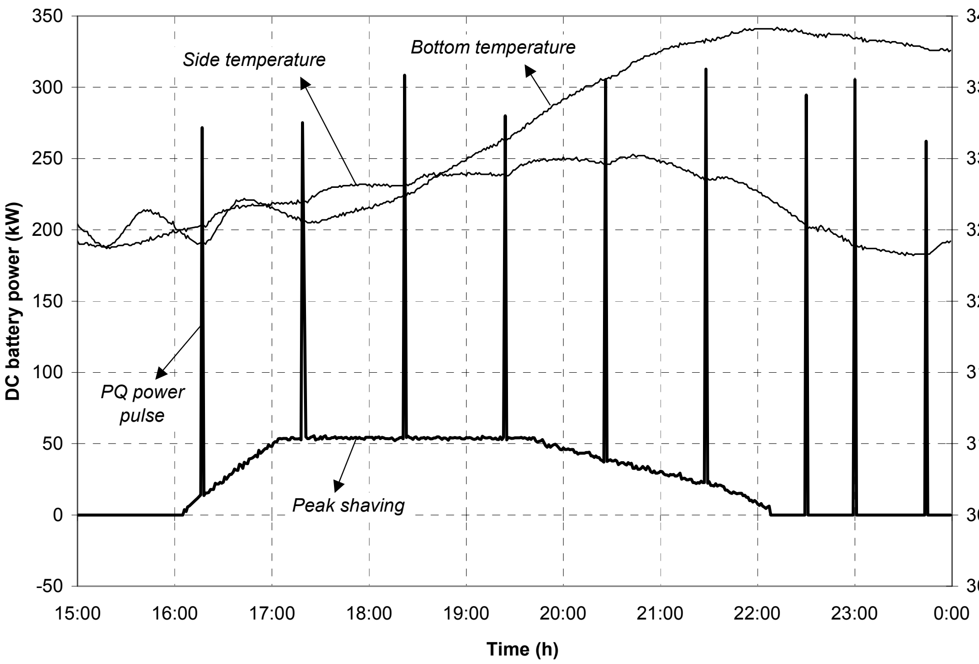

Figure 9. Combined operation-PS with 250kW PQ protection for 30 seconds. The upper two waveforms show the base and the side battery module temperatures.

The trapezoidal PS profile shown in Figure 9 has one-hour ramp up, two and a half hour flat, and three-hours ramp down regions. This discharge profile is optimized for 5 times and 30 seconds PQ protection usage. The reason for increasing the power level gradually at the beginning of the cycle and reducing it towards the end is to maintain the polarization resistance at a desired level.

The top two waveforms in Figure 9 show the side and base temperatures of the battery module. During each PQ event, the side temperature increases around 2-3 ˚C, which is not a very significant increase for an operation that is 5 times the rating. The waveforms indicate the high thermal capacity of the modules and the quality of the heat insulation. The sampling interval of data shown in Figure 9 is one minute.

Figure 10 shows the test result of the response of the system to a power quality event. Only the voltage and current of phases *a* and *b* were plotted to provide visibility of the dynamics. The data during the PQ tests were measured and recorded by the Nicolet Vision, which is a high-speed 16-channel data acquisition instrument. As shown in Figure 10, phase *a* of the source voltage was sagged below 80% of nominal (480V) and initiated the PQ event. The system responded to the disturbance in 2 milliseconds and picked up the load. The load voltages (second trace) and the load currents (bottom trace) show a smooth transition and continuous power flow to the load.

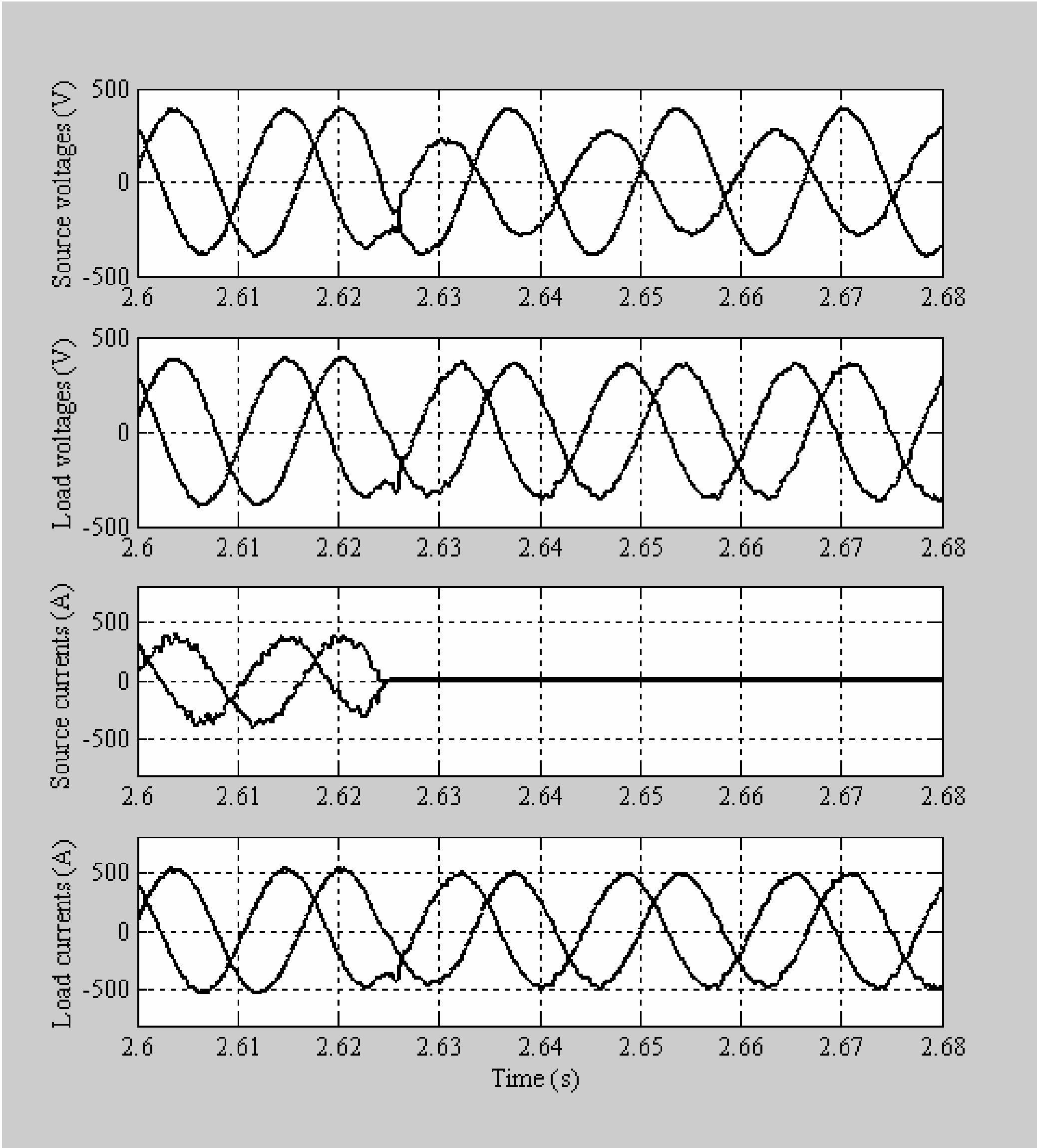

Figure 10. The system response to a PQ event test during a peak shaving cycle. The top trace shows only the two phases (*a, b*) of the power system, the second trace is the load voltages, the third trace is the source currents and the bottom trace is the load currents.

Comparison of the load currents and source currents indicate peak shaving before the PQ event. During this test, the load was set at 300kW and the system was peak shaving at 100kW correspondingly the power coming from the source is 200kW. Furthermore, the load currents (bottom trace in Figure 10) verify the performance of the system in UPS applications rated at 300kW.

V.3.1 ITI Curve (CBEMA) Compliance Tests [3]

Compliance of the system to the ITIC criteria is very important for two reasons. First, ITIC compliance insures that sensitive equipment used in the critical loads can ride through nominal power system disturbances [3], which is the primary purpose of all UPS systems. Secondly, any noise or voltage spikes created such as by a capacitive bank switching should not cause the system to pick up the load by tripping off the SCR

switch. The major drawback of nuisance tripping is the unneeded use of energy from the batteries. According to the operational state diagram, PCS stays in PQ mode for a minimum of 5 seconds even though the grid is normal right after the start of the event. For this reason, nuisance tripping of static switch should be avoided. Verification of ITIC compliance was one of the important tasks in the evaluation of the NAS system.
Figure 11 shows the results of the ITIC compliance tests. The straight lines indicate the ITI Curve, the dashed line indicate the PCS grid detection window, the circles show the PCS response, the diamond shapes show the not-responded disturbances, and the triangular shapes show the responded disturbances. The system is not supposed to respond to the disturbances within or near the detection window, which is validated by the test results as shown in Figure 11. The system responded to the disturbances that are out of grid detection window and their responses fall within the ITC curve boundaries. The results also indicate the minimum response time is 0.8ms, which is enough to avoid nuisance trips. The overall results verify that the system response to various sags and swells is well within the ITIC criteria.

VI. CONCLUSIONS

This research shows that the NAS batteries have superiority over other type of energy storage systems in utility applications. Especially the peak power capability of NAS battery is a unique feature that enables systems to be built as multi-functional systems. This future provides the customer with complete solution in one design. Advances in power electronics technology make the design of such a systems possible.
However, the main challenge in the combined systems is to perform all functions at the desired level, system should not compromise one function for the other. Therefore, PQ availability is an important challenge for the multi-function battery system. The test results showed that NAS battery is capable of handling high PQ powers as long as there is sufficient remaining charge. Therefore, peak shaving function of the system should be managed properly to always save some extra energy in the battery so that no PQ event is missed.
Another observation is about the importance of the temperature control. The PQ functionality can be disabled if battery temperature tries to exceed safe operating temperature limits, which may occur near the end of discharge where the temperature is the highest. It has been realized that with advanced controllers, this problem can easily be solved.

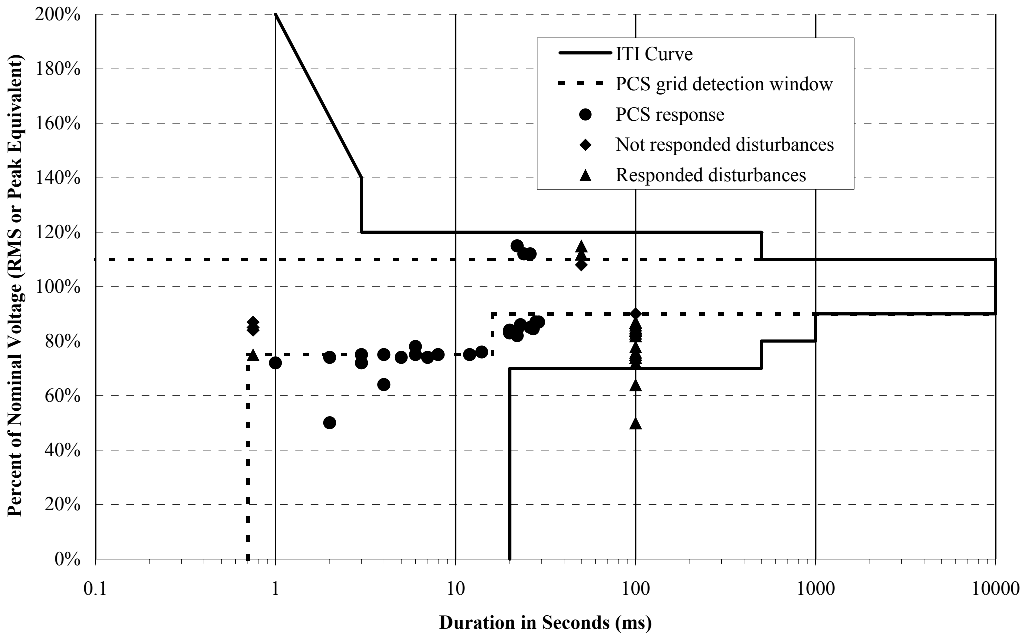

Figure 11. ITIC compliance test results of the NAS Battery system.

Moreover, the tests have also demonstrated that the NAS battery system can meet a wide range of standards and specifications required for multiple function operation. AEP, Department of Energy/Sandia National Lab and EPRI are continuing to monitor the project through a sophisticated monitoring package that will allow further technical and economical assessment of the NAS technology.

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