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# NAS® Battery Demonstration at American Electric Power

## A Study for the DOE Energy Storage Program

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# NAS® Battery Demonstration at American Electric Power

## A Study for the DOE Energy Storage Program

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## Abstract

The first U.S. demonstration of the NGK sodium/sulfur battery technology was launched in August 2002 when a prototype system was installed at a commercial office building in Gahanna, Ohio. American Electric Power served as the host utility that provided the office space and technical support throughout the project. The system was used to both reduce demand peaks (peak-shaving operation) and to mitigate grid power disturbances (power quality operation) at the demonstration site. This report documents the results of the demonstration, provides an economic analysis of a commercial sodium/sulfur battery energy storage system at a typical site, and describes a side-by-side demonstration of the capabilities of the sodium/sulfur battery system, a lead-acid battery system, and a flywheel-based energy storage system in a power quality application.

# Acknowledgement

The authors wish to acknowledge the U.S. Department of Energy, Energy Storage Systems Program for the support of this work. The American Electric Power Company installed and operated the battery system, collected test data, and provided additional support for the study. Partners in the project include NGK Insulators, Ltd., Tokyo Electric Power Company, ABB, Inc., /Sandia National Laboratories, and the Electric Power Research Institute.

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# Nomenclature

| | |
|---|---|
| AEP | American Electric Power |
| BESS | Battery energy storage system |
| BMS | Battery monitoring system |
| CBMA | Computer Business Manufacturer’s Association |
| DAS | Data acquisition system |
| DOD | Depth of discharge |
| ESS | Electrical storage system |
| HVAC | Heating, ventilation, and air conditioning |
| IGBT | Insulated gate bipolar transistor |
| ITIC | Information Technology Industry Council |
| IRR | Internal rate of return |
| MACRS | Modified Accelerated Cost Recovery System |
| Na/S | Sodium/sulfur |
| NPV | Net present value |
| O&M | Operations and maintenance |
| PCS | Power conversion system |
| PQ | Power quality |
| PS | Peak shaving |
| RMS | Root mean square |
| SOC | State of charge |
| TEPCO | Tokyo Electric Power Company |
| TOU | Time of use |
| UPS | Uninterruptible power supply |

# NAS® BESS Performance Demonstration

## Introduction

The first U.S. demonstration of the sodium/sulfur (Na/S) battery technology was launched in August 2002 when a prototype battery energy storage system (BESS) was installed at a commercial office building in Gahanna, Ohio. NGK's NAS® battery was selected as the storage device based on its high energy density, high efficiency, and long life as compared to conventional batteries. ABB of New Berlin, Wisconsin, supplied the power electronics used to convert DC power from the battery to AC power for use by the office park. American Electric Power (AEP) served as the host utility that provided the office space and technical support throughout the project. The installation was intended to demonstrate the BESS's usefulness to commercial electric utility customers across a range of applications, including power quality (PQ) and peak shaving (PS). This report summarizes the operation of the prototype BESS and provides a number of recommendations for future NAS® BESS installations based upon the lessons learned in Gahanna. Additionally, an economic analysis was developed to gauge the cost effectiveness of the NAS® BESS for the prospective customer-owner. Finally, the demonstration provided a unique opportunity to view NAS® BESS performance relative to two other advanced electrical storage systems (ESSs), each capable of protecting customer loads during utility disturbances.

## System and Load Description

The demonstration system consisted of two NAS® battery modules (see Table 1) each rated at 50 $kW_{ac}$ and capable of supplying 360 $kWh_{ac}$ of energy. The power conversion system (PCS) was designed to provide both high-power/short duration uninterruptible power supply (UPS) functionality, as well as daily demand reduction achieved by storing energy at night (off-peak) and discharging it during the day (on-peak). The demonstration system was monitored for 18 months.

**Table 1. NAS Module Ratings**

| | |
|---|---|
| Pulse Power | 250 $kW_{ac}$ (30 sec) |
| Rated Power | 50 $kW_{ac}$ (7.2 hours) |
| Energy | 360 $kWh_{ac}$ |
| Dimensions | 2200 W x 1762 D x 640 H (mm) |
| Weight | 3600 kg |

The system was installed at an office complex with low loads. The loads were not critical, as in manufacturing or data handling operations, and a key tenant had departed just prior to installation so the daily load was not as high as expected. Additionally, only a portion of the building load (outlets, lighting, and part of the heating, ventilation, and air conditioning [HVAC] system) was protected by the system. The majority of the HVAC system (which represents a significant portion of the load) was not protected. In a true commercial application, the NAS® BESS would have been installed to protect critical power circuits for a PQ application and/or those circuits serving most of the load for a PS application. Consequently, while the demonstration site and customer load were not ideal for demonstrating the system's full capacity for peak shaving or its usefulness in mitigating PQ issues on critical circuits, they were sufficient to demonstrate system operation for both PQ and PS applications.

# Data Acquisition

The one-line diagram of the demonstration installation is shown in Figure 1. AEP implemented a data acquisition system (DAS) to gather data from several sources. Three General Electric Model kV2 electronic energy meters (one each located on the grid, the building load, and the auxiliary load) recorded various AC power parameters (including voltage, current, and total harmonic distortion) once per minute. Additionally each battery module contained a battery monitoring system (BMS) that recorded various battery-related parameters (current, voltage, charging status, and battery temperature) once per minute. Data from these five sources was stored a Microsoft SQL Server database. AEP provided the data to Endecon Engineering and Norris Energy Consulting on CD-R for analysis; some supplemental data was also sent via internet.

Three additional sources of data were monitored by AEP engineers:

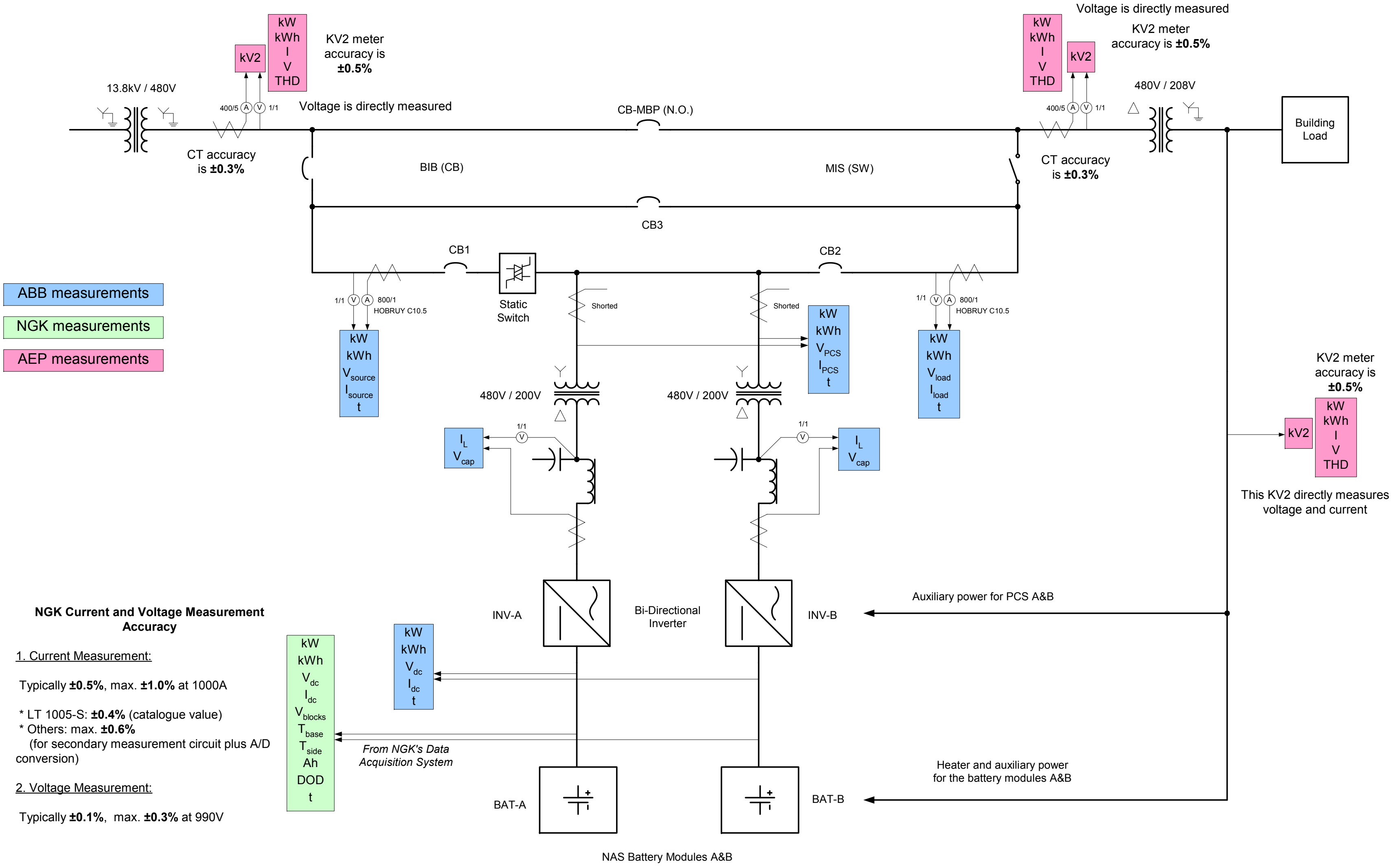
- A power quality monitor (model PP1 manufactured by Dranetz-BMI) was installed for the multi-technology comparison (described later in this report). This device provided an independent record of AC voltage and current waveforms during AC power disturbances.
- The PCS display was used to indicate faults and PCS operating status. (Data acquisition specific to the PCS was not implemented for the demonstration.)
- An additional kV2 meter was used to sample the total building load every 15 minutes.

Although the data from these sources was not recorded into the SQL Server database, it was referred to in the engineers' operations and maintenance (O&M) notes and these notes were used during data analysis.

# System Operation

BESSs are suitable for use in a wide variety of utility and customer applications. Batteries (when packaged as a UPS) are commonly used to stabilize the power supply to critical loads (such as computers). Another potential use, however, is displacing energy use from a high-cost time interval to a lower-cost time interval or, alternatively, to use energy stored during off-peak times to support peak loads and thereby reduce peak demand at the utility meter (the PS application). The UPS (or PQ) function typically requires high power output for a relatively short interval, while PS applications require a lower power output for a longer interval.

The NAS® BESS demonstration system was designed to support both PQ and PS applications simultaneously, which distinguishes it from other BESS technologies. The system design allows the operator to choose from a selection of predefined operating regimes (discharge/charge profiles) that optimize the system for different amounts of expected PQ and/or PS activity. Each of these regimes has been pre-designed to ensure at least some minimum level of PQ protection. Thus, the system can supplement utility power during daily peak demand times, while remaining ready to respond to power disturbances on the utility distribution system.



**NGK Current and Voltage Measurement Accuracy**

1. Current Measurement:

Typically **±0.5%**, max. **±1.0%** at 1000A

* LT 1005-S: **±0.4%** (catalogue value)
* Others: max. **±0.6%**
(for secondary measurement circuit plus A/D conversion)

2. Voltage Measurement:

Typically **±0.1%**, max. **±0.3%** at 990V

**Figure 1. AEP NAS demonstration project one-line diagram.**

## NAS® BESS Operating Regimes

The demonstration system was operated in the four different regimes shown in Table 2. These operating regimes were designed to meet the need for various combinations of PQ and PS benefits. The regimes used for the demonstration were selected based on the number of PQ events anticipated, the average frequency and duration of load peaks, and best operating practices for the battery modules. Each change in regime reflects an attempt to more closely match the operating regime to the actual conditions of the demonstration in order to optimize both battery life and the system's response to the load (for both PQ and PS situations) as well as simply to demonstrate the system's ability to operate in the various regimes. The operating regimes were pre-programmed into the NAS® BESS and assigned numerical designations by NGK (the battery manufacturer); consequently, the numerical designations do not represent a chronological sequence.

**Table 2. NAS Operating Regimes Tested**

| Operating Regime | PQ Protection | PQ Factor | PQ Interval | PS Profile Duration | PS DC kWh per battery | # PS Cycles Over Life | Operating Period |
|---|---|---|---|---|---|---|---|
| 3 | 30 sec | 3.0 | 1 hr | 7.3 hrs | 375 | 2500 | Installation to 5/2/03 |
| 1 | 30 sec | 5.0 | 1 hr | 6 hrs | 210 | 1500 | 5/2/03 to 1/29/04 |
| 6 | 60 sec | 3.0 | 1 hr | 9.3 hrs | 375 | 1500 | 1/29/04 to 3/1/04 |
| 7 | 60 sec | 3.0 | 1 hr | 12 hrs | 375 | 1500 | 3/1/04 to 8/1/04 |

In the table, PQ protection specifies the length of time the system will continuously protect the load in the absence of grid power. The NAS® BESS is programmed to provide PQ protection for the following durations: 30 seconds, 60 seconds, 5 minutes, and 10 minutes. For this demonstration only the 30- and 60-second durations were used. Because operating at higher power levels results in a significant rise in operating temperature, the limiting factor for PQ protection is primarily the batteries' maximum operating temperature.

The PQ factor is the multiple of the system's nominal rated power for pulse delivery. For example, a PQ factor of 5 means that the system can deliver 5 times its nominal power rating for the specified duration of PQ protection. This is a self-imposed limit because the actual power supplied during a PQ discharge is determined by the load (which should not exceed the system's power/energy output ratings). It is important to remember that, because the system operates in both PS and PQ modes simultaneously, its nominal energy output rating is actually a range of values based on the operating regime selected, rather than a single value that represents an absolute maximum for energy output. For Operating Regime 7, for example, the system was rated at 50 $kW_{ac}$/500 $Wh_{ac}$. Larger PQ factors or longer PQ protection durations reduce the amount of energy available for PS operation, thus reducing the system's nominal energy rating. Maximizing the system's PS ability (*i.e.,* increasing the energy output) provides only the minimum level of PQ protection (*i.e.,* short duration, low PQ factor).

The PQ interval is the minimum interval between successive full-power, full-duration PQ pulses. A short pulse of 500 kW is possible every hour. Increased PQ protection requires a significant increase in the PQ interval. To provide 5 or 10 minute PQ protection, for example, increases the PQ interval from 1 hour to 12 hours.

The PS profile duration is the length of time the battery is supplying PS power to the load. The profile duration depends on the operating regime selected and is based on a pre-programmed discharge profile for PS operation that includes a 'ramp-up' interval where the battery goes from 0-kW output to the system's nominal rated output; a 'hold' period where the system is constantly delivering power at its rated output value; and a 'ramp-down' interval where the output power is gradually reduced back to 0 kW. The 'PS DC kWh per Battery' column shows the energy delivered from each battery during a PS cycle.

The 'Number of PS Cycles over Life' column reflects the life expectancy of the batteries when operated at a given PQ factor and PQ protection duration. NGK designed the batteries to meet the rather-stringent life-expectancy requirements of Tokyo Electric Power Company (TEPCO), which has been collaborating with NGK in the development and commercialization of the Na/S technology for stationary (*i.e.,* non-vehicle) applications. For example, for a 50-kW/400-kWh system being demonstrated in Japan TEPCO expected the batteries to last for 15 years and 2,250 full charge/discharge cycles based on 8-hour daily PS operation. Indeed, a much larger demonstration system (6 MW/48 MWh) has been operating in Japan for over 7 years. Additionally, although under certain operating regimes the batteries' life expectancy is less than the TEPCO-specified 2,250 cycles, it is well within Weibull statistical parameters for Na/S-based utility batteries.[1,2]

A tradeoff exists between power output and battery life. Higher PQ factors or longer protection durations require lower resistance and thus higher low-end operating temperatures. Higher operating temperatures, however, accelerate cell corrosion and increase cell resistance which shortens battery life. For example, to achieve the (relatively high) PQ factor of 5 shown in Operating Regime 1 the low end of the modules' operating temperature range was purposefully set high.[3] In practice the user would select the higher operating temperatures only if a PQ factor of 5 were actually required because higher temperature operation limits the energy available for peak shaving and shortens battery life. Consequently, when selecting an operating regime it is extremely important to have a thorough knowledge of the type and amount of protection required (*i.e.,* a full understanding of the application) in order to select the regime that provides the optimal balance between available PQ protection and PS capability while maximizing battery life.

## Cycle Definition

A battery cycle represents the basic charge/discharge operation that repeats in a given battery application. The BMS supplied by NGK with each battery module provides a cycle number for each data record but, when used to analyze information such as round-trip efficiency or charge ampere-hours per cycle, these cycle numbers frequently yielded confusing results. For example, the cycle numbers for the two battery modules do not stay in synch because each battery was subjected to unequal numbers of discharges during testing. Additionally, every discharge initiated a new cycle so, when PQ discharges occurred the energy cycle was 'spilled', yielding an excess of discharge energy in the first 'cycle' and an excess of charge energy in the second 'cycle'.

To support cycle-based analysis for the system as a whole, and to obtain data for complete discharge-recharge cycles for the individual batteries, a 'system cycle number' was synthesized. The synthesized system cycle is defined as the time from when the NGK-reported state-of-charge (SOC) drops below

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[1] Braithwaite, Jeffrey and William Auxer in *Handbook of Batteries*, 3rd edition; Linden, David and Reddy, Thomas, Ed; McGraw-Hill: New York, NY; Chapter 40.

[2] At the end of their useful life, system batteries are returned to NGK for recycling.

[3] Battery operating temperatures were lowered (by changing the operating regime) beginning in January 2004.

100% on either battery, until both batteries reach 100% SOC. The next cycle begins when the SOC drops below 100% again. A summary of cycle data is provided in Appendix A.

# PS Operation

PS operation requires relatively large energy capacity but results in minimal degradation of capacity over the long-term (*i.e.,* the batteries have a relatively long cycle life when used primarily for peak shaving). Various aspects of the demonstration system's PS performance are discussed below.

## System Charge/Discharge Profiles

This demonstration was not intended to dispatch power in response to real-time load signals (*i.e.,* it was not a 'load following' system). Rather, the charge/discharge cycle profiles were defined in the system controller to represent 'typical' work-week-based charge/discharge cycles that might be useful to a customer. The weekday (Monday through Thursday) charge/discharge cycle begins when the daily discharge begins (just before 7:00 a.m.) and continues until the first discharge is initiated on the following day. Weekend cycles start on Friday and last for three days (from Friday morning until the weekday cycle begins the following Monday morning). Note that the discharge is ramped up to its maximum level and later ramped back down to zero. Based on best practices for the Na/S technology and for the design of the NGK batteries, charging begins abruptly but ends with a 'capping-off' effect with a period of pulsed charging at half the maximum charge rate. The measured output for a typical weekday charge/discharge cycle for two different profiles (Operating Regimes 6 and 7) is shown in Figure 2 and Figure 3, respectively. The manufacturer designed both profiles to deliver a nominal 720 $kWh_{ac}$ and both were within ±3% of the design specification.

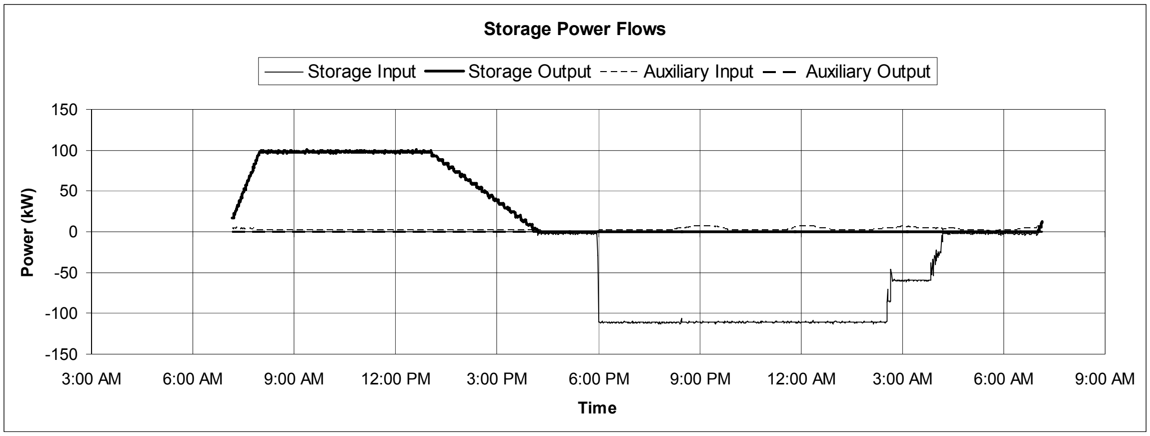

**Figure 2. Regime 6 storage charge/discharge profile (measured 2/5/2004).**

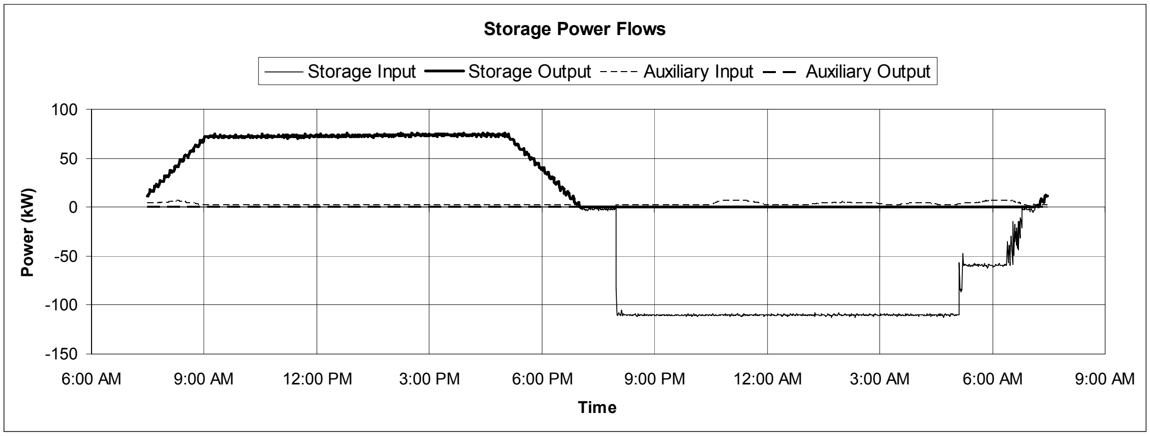

**Figure 3. Regime 7 storage charge/discharge power profile (measured 5/19/2004).**

The measured charge and discharge energy for these profiles is shown in Table 3. Charge energy and discharge energy per cycle are indicators of the system's effectiveness in shaving peak loads; the difference between these quantities is the energy losses (or energy cost). The system's charge and discharge energy were measured using the AEP-supplied kV2 meters which are accurate to within ±0.5% which results in a maximum margin of error of ±1.0%. The two columns show the accumulated energy quantities (charge and discharge) as measured between the two power meters on either side of the system (not including auxiliary loads). System losses (*e.g.,* battery losses in the charge/discharge cycle, PCS conversion losses, and static switch losses) are reflected in the difference between these two figures.

**Table 3. Sample Cycle Storage Energy (in kWh$_{ac}$) for Two Tested Regimes**

| Regime | Charge Energy | Discharge Energy | Charge Energy Cost | Auxiliary Load Cost | Total Energy Cost | Auxiliary Load Cost Percentage |
|---|---|---|---|---|---|---|
| 6 | 1050 kWh | 699 kWh | 351 kWh | 66 kWh | 417 kWh | 16% |
| 7 | 1100 kWh | 726 kWh | 373 kWh | 68 kWh | 441 kWh | 15% |

Power for the auxiliary load was supplied on a separate branch of the circuit so that the effect of the auxiliary equipment on overall system efficiency could be measured and so that the efficiency of the NAS® battery could be assessed independently of the BESS as a whole. The auxiliary loads include the PCS (comprising mainly internal fans, control devices, and the static switch), the NAS® battery controllers, and the heaters used to maintain battery temperature when the battery is not generating enough internal heat to stay at the required minimum operating temperature (which represent the largest portion of the total auxiliary load). The total energy consumed by the auxiliary equipment is the auxiliary load cost. The total energy cost is the energy required to charge the batteries plus the energy used by the auxiliary loads.

## System and Charging Efficiency

Two measures of efficiency are presented below: charging efficiency (the 'round-trip' AC-AC efficiency of the NAS® battery and the PCS) and system efficiency (the 'round-trip' AC-AC efficiency of the battery, the PCS, and the auxiliary loads). The battery efficiency (the 'round-trip' DC-DC efficiency of the battery only) was measured but, for the purposes of evaluating the NAS® BESS as a system, only the system efficiency and the charging efficiency are discussed here. Each is computed using energy out of the system divided by energy into the system between fully charged states (discharge-charge cycles). Table 4 shows the charging and system efficiencies for Operating Regimes 6 and 7. Due to combining multiple sources of error, the maximum margin of error for the charging efficiency is approximately ±2.0%, but a typical margin of error may be as low as ±1%. System efficiency margin of error ranges from ±1.5% to ±3%.

**Table 4. Efficiency Results for Sample Cycles**

| Regime | Charging Efficiency | System Efficiency |
|---|---|---|
| 6 | 64-68% | 57-63% |
| 7 | 65-69% | 57-63% |

Figure 4 shows the long-term system efficiency over the seven-month period from February to August 2004. The figure shows the ratio of energy output relative to energy input for the whole system, including all auxiliary loads and losses. The trend is stable over the period of study. System efficiencies for a conventional (*i.e.,* non-dual use) PS application are expected to be about 70%; the lower values shown in the table are largely an indication of the penalty for the dual-use (PS/PQ) application.

To accommodate dual-use, a static switch was used to isolate the load from the utility during a PQ event (a momentary voltage sag or outage). When utility power has been normalized (typically after a few seconds), the system re-synchronizes with the utility and closes the static switch. In this manner, the system is always available for both PQ and PS operation. By serving loads through a static switch, however, losses associated with voltage drops in the switch are incurred continuously, whether the battery is charging, discharging, or is idle. These losses, although small (typically only a few percent), add up and can become significant over long periods of continuous operation.

Additionally, while the project team expected a system efficiency of approximately 70% (based on previously published information[4]), the overall system efficiency was not addressed in the initial system specification. If system efficiency had been specified, the target could have been met by optimizing PCS size and optimizing the controls of the auxiliary loads. For additional discussion see the *Lessons Learned* section, below.

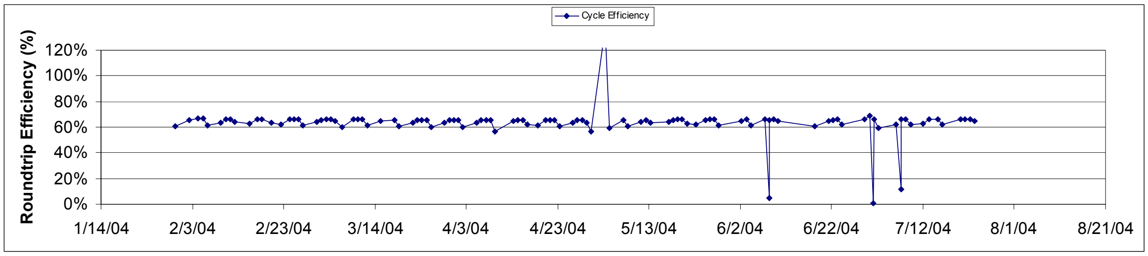

Figure 4. Long-term system efficiency trend.

## DC Data for Battery and PCS

DC energy flow in and out was intended to be estimated using the data recorded by the NGK BMS for each battery. In principle, this DC data could be used to isolate the battery component efficiency from the rest of the system (PCS, static switch, auxiliary loads, etc.). This detailed analysis was not performed, however, because of measurement uncertainty.

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[4] SAND2003-2387, *Long- vs. Short-Term Energy Storage Technologies Analysis: A Life-Cycle Cost Study.*

The accuracy of the battery current measurements is related to the current sensor ratings; the sensors were sized for the peak current expected during PQ operation with the largest possible PQ factor—5, which resulted in a 5-A uncertainty (0.5% of 1000 A). This uncertainty was too large to obtain sufficiently accurate estimates of battery cycling efficiency for the current levels typically seen in PS operation (approximately 80 A). The uncertainty of the measurements was confirmed in a detailed evaluation of the sensors using independent measurements. Consequently, performance calculations that would have depended upon accurate DC data (such as battery and PCS performance) are not included in this report. A more detailed discussion of the DC data issues is presented in Appendix B.

## State of Charge and Depth of Discharge

SOC is the percent of the battery's rated capacity that is available at a given time. Battery SOC was computed and recorded by each battery's BMS based on the amp-hour flow in and out of the battery relative to rated capacity. During each charge cycle SOC was driven to 100% and then slightly overcharged based on best operating practices for charging the batteries (the SOC reading was clipped at 100%). Subtracting the minimum SOC from 100% gives the depth-of-discharge (DOD).

Lead-acid batteries typically are discharged to 50% for cycling applications (*e.g.,* peak shaving) and to 80% for less-frequent, high-power applications (*e.g.,* power quality support). The results in Table 5 show that the batteries in the NAS® BESS were discharged to a significantly greater DOD than would be practical for lead-acid batteries. The battery capacity is almost completely spent in these cycles. Battery 1 has additional remaining capacity at the end of discharge relative to Battery 2. The fact that Na/S batteries can sustain this level of discharge indicates that unlike lead-acid batteries, an ESS using the Na/S technology would not have to be significantly over designed for the application.

**Table 5. Battery Depth-of-Discharge for Sample Cycles.**

| Regime | DOD | |
|---|---|---|
| | Battery 1 | Battery 2 |
| 6 | 90% | 96% |
| 7 | 90% | 94% |

## Thermal Control

Na/S batteries must be operated at a sufficiently high temperature to keep the active electrode materials in a molten state and to ensure adequate ionic conductivity through the electrolyte. Typically the operating temperature range for Na/S batteries is 290-390ºC. A more practical operating temperature range (310-350ºC) has been defined based on the power levels usually required of the technology and optimizing the batteries' service life.[5] As discussed in the *Operating Regimes* section, above, trade-offs exist between available power for PQ operation, operating temperature, and available energy for PS operation. Consequently, each operating regime has a prescribed temperature range. The controls for the battery heater are set to keep the batteries at the prescribed minimum temperature for the operating regime (305ºC for Operating Regimes 6 and 7).

Thermal monitoring of each battery is implemented by the battery's BMS using two sensors. Table 6 shows the batteries' operating temperature range during the sample cycles. The sample cycles analyzed here occurred mid-week (when the batteries were active for peak shaving); thus the battery temperature does not reach the same low temperatures observed over weekend cycles. Temperature

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[5] Braithwaite, Jeffrey and William Auxer in *Handbook of Batteries*, 3rd edition; Linden, David and Reddy, Thomas, Ed; McGraw-Hill: New York, NY; Chapter 40.

variation over time is shown in Figure 5 for Battery 1; it is apparent that the temperature ranges do not vary significantly.

**Table 6. Bottom Temperature Averages and Extremes**

| Regime | Heater Set Points | Battery 1 (typical) | | |
|---|---|---|---|---|
| | | Minimum | Average | Maximum |
| 6 | 305ºC | 319ºC | 333ºC | 350ºC |
| 7 | 305ºC | 321ºC | 331ºC | 346ºC |

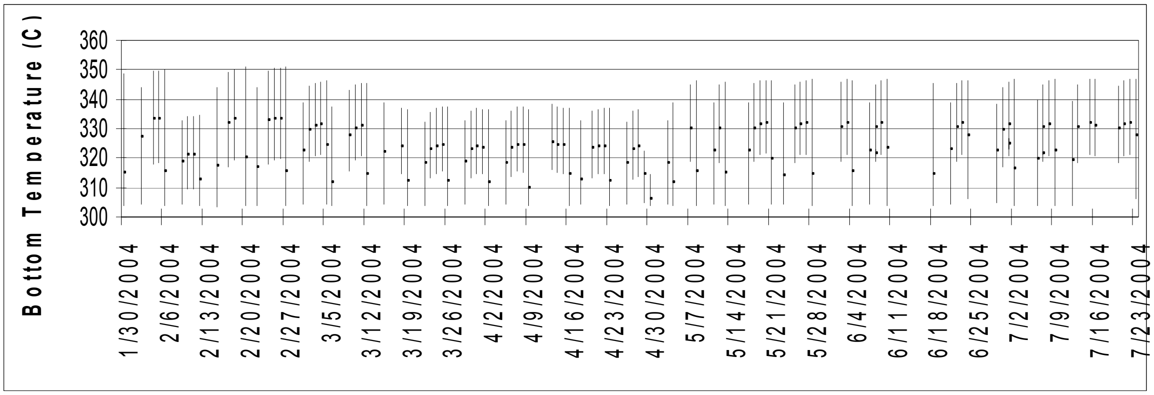

**Figure 5. Battery 1 bottom temperature variation.**

# PQ Operation

## PQ Events and Utility Faults

PQ events can include utility outages, voltage excursions, frequency excursions, and voltage and current harmonic content. For this study, the load-side and grid-side kV2 meters were configured to report each voltage sag and swell event and the event duration. Data reported here represents the period from February 2 to June 14, 2004.

The Information Technology Industry Council (ITIC), formerly the Computer Business Manufacturer's Association or CBMA, has defined limits of acceptable voltage level depending on length of outage.[6] These limits are typically represented as a curve on a linear-vs.-log graph; one point is shown for each outage. Points that occur above the upper limit or below the lower limit are considered to be significant enough to be considered undesirable power quality. Figure 6 shows the curve for the grid-side meter data. Figure 7 shows the curve for the corresponding load-side meter data. Twenty-five events are outside the ITIC-defined limits for the grid meter, while none are outside the limits from the load meter, which indicates that the NAS® BESS provides a significant improvement in power quality to the load.

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[6] ITIC Curve, 1997 based on IEEE Standard 1100-1999, *IEEE Recommended Practice for Power and Grounding Electronic Equipment.* IEEE Press, 1999.

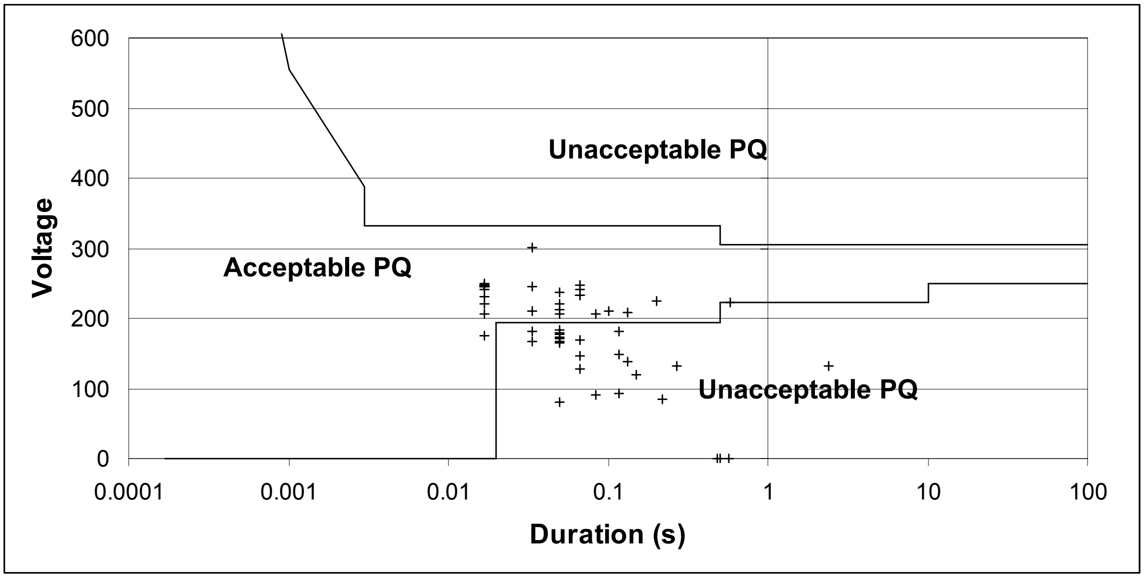

Figure 6. Grid-side PQ events (1997 ITIC Values).

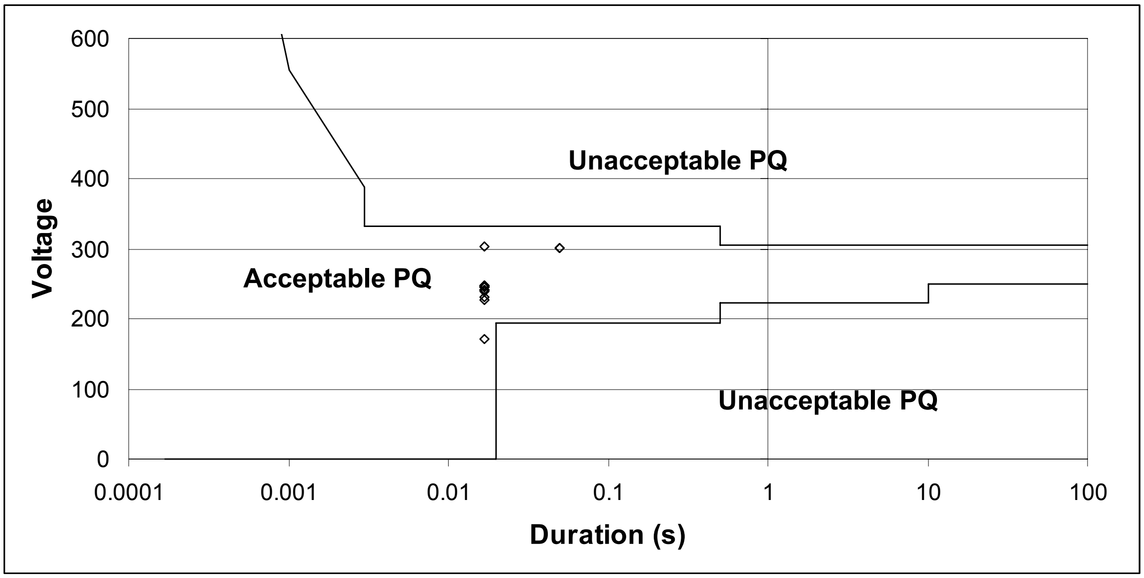

Figure 7. Load-side PQ events (1997 ITIC Values).

# Lessons Learned

The demonstration met its principal objectives, namely, the demonstration of the technology in a utility environment and the validation of multiple operating modes. The system has successfully shaved peak loads and protected the facility load from grid disturbances. To accomplish these objectives, however, the NAS® BESS was often operated at higher low-end temperatures than necessary, which allowed it to provide higher power (PQ) capability for short durations. This short-term rating exceeded that required for continuous PS operation for the load profile; it represented a scenario in which a larger facility could use the system to protect its full load during utility disturbances, while shaving only the peak power consumed. This enhanced power capability served to demonstrate the robustness of the system, albeit with some accelerated temperature-related aging and cycle-life consumption. In the course of this analysis, however, a number of lessons were learned that may be applicable for future projects and systems of similar scope.

## System Efficiency

The overall system efficiency, if critical, should be addressed in the initial system specification. For this demonstration, efficiency requirements were not specified in the design phase and performance was not as expected. There are several reasons for this: (1) the static switch used for PQ operation drew a continuous load, a loss that is not included in PS-only designs; (2) the PCS size was not optimized, as discussed below; and (3) the auxiliary loads and load controls were not designed to ensure maximum system efficiency. In contrast, the emphasis for the demonstration was on system robustness that would serve to verify the operating extremes of PQ and PS functionality.

## Nominal versus Peak Efficiencies

For this project, the PCS converter efficiency was designed to meet the peak (500 kW) power capabilities, and PCS efficiency was measured at 95% in the factory. However, in the PS operating mode, PCS throughput was much lower (100 kW and below), and the reduced part-load efficiency was observed in this analysis. Had the PCS design been optimized for a level closer to 100 kW, the overall system efficiency would have been improved.

## Data Monitoring Systems

The DC measurements used by the control system were inadequate for treatment in the performance analysis. This was true for a number of reasons, including the requirement that current sensors would be capable of reaching power levels up to five times the system's steady-state rating. Because normal system operation always involves a wide variation operating current levels (approximately 80 A for PS operation and up to 1000 A for PQ operation at a power factor of 5), accurate estimates of battery efficiency would require special instrumentation (a separate set of sensors) and the exclusion of PQ operation (which was not an option for this demonstration). Had a separate set of sensors been employed for lower power levels, a more detailed set of performance data could have been obtained, including a breakdown of DC components.

The power metering was performed at a sub-building level and, consequently, did not record the total building load. It is possible that the total building load would have a profile with more energy consumed in the peak period relative to off peak (for example, from the facility's HVAC system). Had the total building load been measured, it is possible that PS operation would have been more closely matched to the load shape and thus more economically advantageous.

## Economic Impact of PS Operating Regimes

Finally, the demonstration showed that NAS® BESS operating regimes should be adjusted to take into account the customer's electric tariff and load profile. Whether the tariff structure employs demand charges or time-of-use (TOU) energy charges, the profile should be designed to maximize the PS benefit. Alternatively, a real-time dispatch algorithm could be used to follow minute-by-minute changes in load. The economic impact of the operating regimes is discussed in greater detail in the following section, *NAS® BESS Economic Analysis*.

# NAS® BESS Economic Analysis

In general, electric utilities use a combination of two sets of charges (or tariffs)–demand charges and energy charges–to determine a customer's monthly electric bill. In theory, demand charges represent a utility's fixed costs for providing a given level of power to a customer and energy charges represent the variable portion of the customer's electric bill (how much energy, in kWh, was used). Demand charges are based on the maximum amount of power used during a given time period and are judged against a baseline that is considered the 'normal' use for customers of a given size (*i.e.,* load). Consequently, demand charges vary month to month based on the difference between the customer's peak use and their nominal (normal) use. The higher the peak use, the higher the demand charge. The more such demand peaks are reduced, the greater the monthly demand-charge savings that can be realized. Energy charges are based on the customer's total cumulative energy use (the number of kWh supplied) per month. Electric utilities can charge either a flat fee per kWh used or can adopt a TOU rate structure that charges customers more per kWh for energy supplied during peak demand times (*e.g.,* weekday afternoons in summer in hot locations such as southern California) and less for power supplied during off-peak hours (at night and/or on weekends, in the above example, when business use of air conditioning is generally reduced). Under such TOU rate structures, energy charges vary according to the number of on-peak and off-peak (and in some cases partial- or mid-peak) kWh purchased. Under such rate structures, the more on-peak power consumption that can be displaced to off-peak hours, the greater the cost savings.

## Economic Impact of the NAS® BESS at the Demonstration Site

To provide the most effective economic analysis of the system's peak-shaving capabilities, ideally the NAS® BESS would have been installed at a customer site with significant load peaks and a tariff structure with either high on-peak energy prices or a high demand charge. The demonstration site, however, was not selected with either of these attributes in mind; rather, it was selected as a convenient test site owned by AEP that provided utility test engineers full access to the system and testing flexibility. Additionally, the pre-programmed operating regimes were designed to represent 'typical' customer loads and thus were not customized for the load at the demonstration site. The results presented in this section, therefore, are not the optimal results that the NAS® BESS is capable of achieving as they do not represent a system control strategy optimized for the load. Indeed, as discussed above, part of the performance demonstration involved changing the operating regime in an attempt to maximize system performance by finding the pre-programmed regime that worked best for the load at the demonstration site. Consequently, it is of limited use to quantify the economic impact of using the system for peak shaving based on this installation alone. Nevertheless, this section describes the potential economic benefits that could be realized by using the system to shave peaks at the demonstration site. A more thorough investigation of the system's potential economic benefits is provided in subsequent sections.

Utility definitions for on-peak and off-peak hours, as well as the associated tariffs, can vary widely even for different geographical areas served by the same utility. In the examples below, two 'scenarios' are defined based on different on- and off-peak hours. These examples do not represent AEP's actual tariffs for the Gahanna demonstration site, but are used for illustrative purposes only. Figure 8 shows the demand profiles for the supply (the grid and the NAS® BESS) and the load for

Operating Regime 6 (higher peak power, shorter duration PS discharge). In this graph, the system is clearly reducing grid power draw in the morning; the power draw increases significantly starting around 6:00 p.m. when the battery shifts from discharge to charge. As shown in Table 7 and Table 8, a 6-hour (1:00 p.m. to 7:00 p.m.) peak-demand interval obtains on-peak energy reduction but demand is increased in both on-peak and off-peak times. A 14-hour (7:00 a.m. to 9:00 p.m.) peak-demand interval reduces the morning peak, but also sees the charging load beginning at 6:00 p.m. (*i.e.,* the battery is being charged for 3 hours with on-peak power).

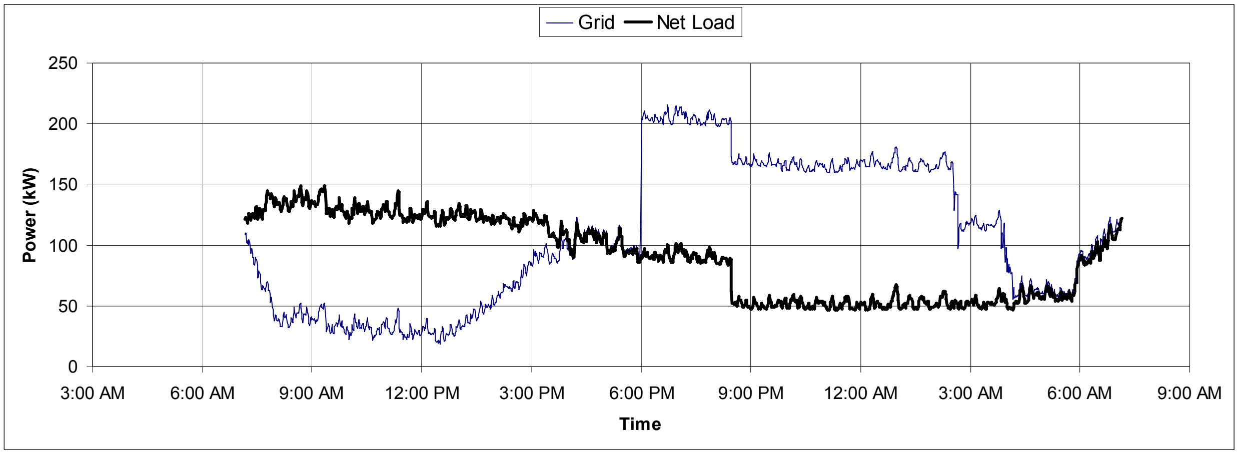

**Figure 8. Load and grid profiles for Regime 6 sample cycle.**

**Table 7. Simulated Energy Charge Reduction for Regime 6 Sample Cycle**

| | Scenario 1<br>Peak Hours = 7 a.m. to 9 p.m. | | | | Scenario 2<br>Peak Hours = 1 p.m. to 7 p.m. | | | |
|---|---|---|---|---|---|---|---|---|
| | On-peak | | Off-peak | | On-peak | | Off-peak | |
| | kWh | Reduction | kWh | Reduction | kWh | Reduction | kWh | Reduction |
| **With BESS** | 1256 | 21% | 1324 | -129% | 619 | 5% | 1961 | -30% |
| **Without BESS** | 1585 | | 578 | | 652 | | 1511 | |

**Table 8. Simulated Demand Charge Reduction for Regime 6 Sample Cycle**

| | Scenario 1<br>Peak Hours = 7 a.m. to 9 p.m. | | | | Scenario 2<br>Peak Hours = 1 p.m. to 7p.m. | | | |
|---|---|---|---|---|---|---|---|---|
| | On-peak | | Off-peak | | On-peak | | Off-peak | |
| | kW | Reduction | kW | Reduction | kW | Reduction | kW | Reduction |
| **With BESS** | 215 | -45% | 181 | -56% | 215 | -61% | 214 | -44% |
| **Without BESS** | 149 | | 116 | | 134 | | 149 | |

Figure 9 shows the demand profiles for the grid and the load for Regime 7 operation (lower power, longer duration PS discharge). In this graph, the grid power draw is still clearly reduced in the morning and increased at night. The discharge profile is more closely aligned with the 1:00 p.m. to 7:00 p.m. on-peak interval, but the charge time still overlaps the 7:00 a.m. to 9:00 p.m. on-peak interval in the evenings. As shown in Table 9 and Table 10, both on-peak intervals obtain an energy benefit with the NAS® BESS in place, but demand charges would only be reduced in tariffs under a 1:00 p.m. to 7:00 p.m. on-peak interval.

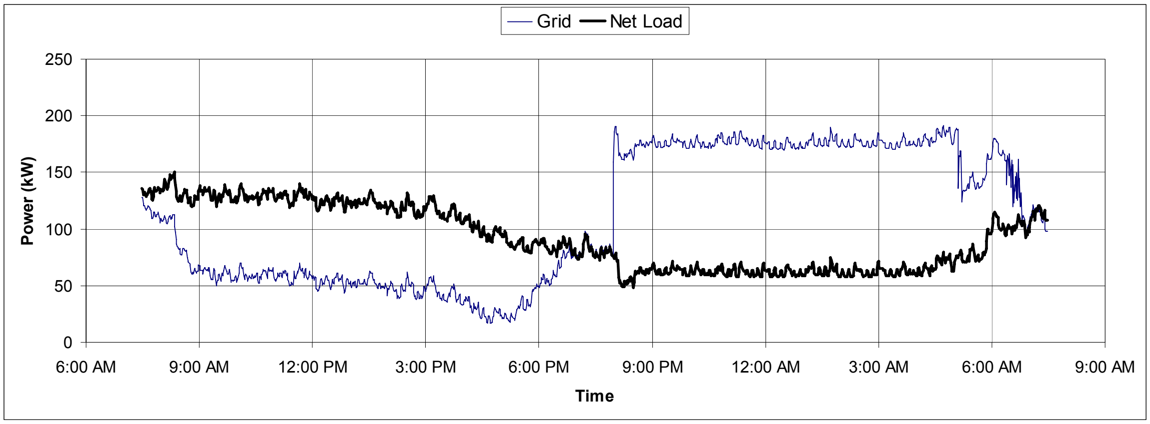

**Figure 9. Load and grid profiles for Regime 7 sample cycle**

**Table 9. Simulated Energy Charge Reduction for Regime 7 Sample Cycle**

| | Scenario 1 Peak Hours = 7 a.m. to 9 p.m. | | | | Scenario 2 Peak Hours = 1 p.m. to 7 p.m. | | | |
|---|---|---|---|---|---|---|---|---|
| | On-peak | | Off-peak | | On-peak | | Off-peak | |
| | kWh | Reduction | kWh | Reduction | kWh | Reduction | kWh | Reduction |
| **With BESS** | 956 | 38% | 1706 | -149% | 267 | 57% | 2395 | -50% |
| **Without BESS** | 1536 | | 685 | | 627 | | 1595 | |

**Table 10. Simulated Demand Charge Reduction for Regime 7 Sample Cycle**

| | Scenario 1 Peak Hours = 7 a.m. to 9 p.m. | | | | Scenario 2 Peak Hours = 1 p.m. to 7 p.m. | | | |
|---|---|---|---|---|---|---|---|---|
| | On-peak | | Off-peak | | On-peak | | Off-peak | |
| | kW | Reduction | kW | Reduction | kW | Reduction | kW | Reduction |
| **With BESS** | 191 | -27% | 192 | -67% | 85 | 37% | 192 | -28% |
| **Without BESS** | 150 | | 115 | | 134 | | 150 | |

These examples show that for both operating regimes the charge duration is too long to be compatible with the off-peak times of the 7:00 a.m. to 9:00 p.m. tariffs; and for the 1:00 p.m. to 7:00 p.m. tariffs, the 12-hour discharge is reducing 6 hours of off-peak time (which must then be recharged with associated losses). Failing to capture the benefit of on-peak demand reduction is a significant weakness in the existing operating regimes. Because the load at the demonstration site peaks in the morning, the existing discharge schedule could capture the desired peak power demand reduction during the 7:00 a.m. to 9:00 p.m. on-peak interval if the charge cycle were delayed until after 9:00 p.m. If the system is to be operated under a tariff using the 1:00 p.m. to 7:00 p.m. on-peak interval, however, the discharge start time would have to be delayed until approximately 12:30 p.m. (the charge start time could remain at 8:00 p.m.). Additionally, when the before and after schedules were compared around the beginning of April, it was noted that the scheduling control software does not incorporate daylight savings time adjustments, which adds to the manual maintenance required to keep PS operation scheduling synchronized with TOU tariffs.

The charge schedules (*i.e.,* charge and discharge start and stop times) that were used in these examples are adjustable, but the choice of schedule must be compatible with the chosen operating regime (which specifies the *duration* of charge and discharge). With both operating regimes shown here, the net result is an overall increase in demand for the day and it is obvious that the building load at this site does not represent a good match for a peak-shaving technology. It is also clear that to use the

NAS® BESS optimally, the system should have a means of customizing the operating regimes to match the demand characteristics of the site at which it is installed.

## Scope of the General Economic Analysis

The dual functionality of the NAS® BESS is accompanied by dual economic benefits. For PQ applications the economic benefit is the avoided cost of accumulated power disruptions which may include costs associated with lost production, labor downtime, equipment failures, equipment maintenance, and other costs that would be incurred in a power surge, sag, or outage. In addition to the avoided costs provided by the PQ function, the customer can use the PS mode to reduce daily and monthly peak-power consumption, thereby offsetting utility demand and energy charges. Initially the economic analysis of the NAS® BESS was intended to assess the system using the Gahanna experience as a baseline but this approach was abandoned primarily for two reasons. First, the Gahanna demonstration employed a prototype technology; many of the cost and performance data that came from the demonstration would not be applicable to a mature product. For example, the maintenance cost would have been unrealistically high because technicians were sent from Japan; a mature commercial product would have local technicians available. The present study attempts to conduct the assessment as if the NAS® BESS were a mature product—that is, capital costs, maintenance costs, and performance assumptions all are based upon expected values for future systems. Second, by using assumptions (*e.g.,* load profiles and commercial tariffs) applicable only to the Gahanna demonstration, the results are of limited use for other locations. Consequently, the economic evaluation was broadened from the site-specific examples described above to the consideration of a more representative commercial customer. Parameters such as load factor, demand charge, and discount rate were used as input for a broad mathematical analysis rather than defined by the Gahanna experience.

## Utility Tariffs

The economic benefits of PS operation accrue from utility bill savings, either in the form of reduced demand charges or savings on TOU energy charges. While it would be convenient to use national or regional pricing averages in this study, an informal survey quickly revealed that electric tariffs for commercial customers are considerably varied in price, structure, and rules of applicability. Consequently, before settling on a ‘typical’ tariff it is helpful to examine the sample tariffs shown in Table 11, which represent a range of geographical areas and utility types (municipal utilities and independently owned utilities). These are summaries including only energy and demand charges; monthly charges, power factor charges, penalties, and other terms are not included. The following observations may be made:

- Demand and energy charges offset one another;
- Most tariffs have seasonal variation, with summer being the most expensive season;
- Not all tariffs include demand charges or on-peak/off-peak price differentials; and
- Some utilities have multiple tariffs available;

Each of these observations is significant in the economic assessment and the use of energy storage, and each is considered separately, below.

**Table 11. Sample Commercial Electric Tariffs**

| | | | Summer | | | Winter | | |
|---|---|---|---|---|---|---|---|---|
| **Utility** | **State** | **Schedule** | **Demand ($/kW)** | **On-peak ($/kWh)** | **Off-peak ($/kWh)** | **Demand ($/kW)** | **On-peak ($/kWh)** | **Off-peak ($/kWh)** |
| PG&E | CA | Medium General Service (Schedule A-10) | 6.91 | 0.131 | 0.131 | 2.09 | 0.095 | 0.095 |
| PG&E | CA | Medium General Service (Schedule A-10 TOU) | 6.91 | 0.162 | 0.118 | 2.09 | 0.098 | 0.092 |
| PSE&G | NJ | General Lighting and Power (Schedule GLP) | 13.82 | 0.085 | 0.085 | 6.07 | 0.093 | 0.093 |
| AEP (Texas Central) | TX | General Service | | 0.109 | 0.109 | | 0.101 | 0.101 |
| SRP | AZ | General Service (Rate E-36) | 3.54 | 0.069 | 0.069 | 1.79 | 0.060 | 0.060 |
| AEP (Ohio Power) | OH | General Service Non-demand (Rate GS-1) | | 0.048 | 0.048 | | 0.048 | 0.048 |
| AEP (Ohio Power) | OH | General Service Time-of-Day (Rate GS-TOD) | | 0.072 | 0.025 | | 0.072 | 0.025 |
| LADWP | CA | General Service Primary (Rate A-2 A) | 16.49 | 0.051 | 0.051 | 15.33 | 0.051 | 0.051 |
| LADWP | CA | General Service Primary TOU (Rate A-2 B) | 11.34 | 0.059 | 0.046 | 10.61 | 0.059 | 0.046 |
| CL&P | OH | Large Time-of-Day (Rate 58) | 10.14 | 0.084 | 0.065 | 10.14 | 0.084 | 0.065 |
| FP&L | FL | General Service Non-Demand (GS-1) | | 0.084 | 0.084 | | 0.084 | 0.084 |
| FP&L | FL | General Service Demand (GSD-1) | 8.16 | 0.053 | 0.053 | 8.16 | 0.053 | 0.053 |
| FP&L | FL | General Service Demand TOU (GSDT-1) | 8.16 | 0.073 | 0.047 | 8.16 | 0.073 | 0.047 |

## Demand and Energy Charges in Rate Design

Utility rates are designed to recover the cost of service (*e.g.,* commodity prices and capital infrastructure). Generally, the cost of the commodity (*i.e.,* the cost to produce electrical energy) is passed on to the customer in the energy component of the rates; the costs of providing the capacity to generate, transmit, and distribute electricity may be recovered through either energy charges or demand charges. Because infrastructure costs are related to the peak capacity provided by the utility, it is natural to incorporate them in demand charges which, in principle, measure the customer's allocation of capacity requirements. In cases where demand is not metered, however, the infrastructure costs are recovered through energy charges. An example of the trade-off between demand charges and energy charges in recovering infrastructure costs can be seen in the FP&L tariffs. Rate GS-1 has no demand charge and a fixed energy charge of $0.084/kWh. Rate GSD-1 has a demand charge of $8.16/kW, but lower energy charges, fixed at $0.053/kWh. These two tariffs provide equivalent cost recovery to the utility.

The importance of this trade-off for storage is twofold: first, customers with storage who select the tariff with higher demand charges are able to obtain lower energy prices. Second, because the capacity costs are recovered through the demand charge, the purpose of TOU differential energy pricing is reduced. Consequently, the TOU energy differential is generally less than tariffs without demand charges, and sometimes they are not available at all. For example, AEP Ohio rate GS-TOD (without a demand charge) offers an on-peak/off-peak ratio of 2.88, while the FP&L rate GSTD-1 (with a demand charge) offers a ratio of only 1.6. While this is not intended to be an exhaustive survey of tariffs nationwide, it would be unusual to find locations combining both high demand charges with high price differentials.

## Seasonal Variation

Many of the tariffs, especially those with a demand-charge component, have different prices for summer versus winter seasons. For example, PG&E Schedule A-10 has a summer demand charge that is over three times the winter demand charge; its summer energy prices are 38% higher than its winter energy prices. In evaluating the viability of storage, these seasonal variations must be considered. It is common to find high demand charges only applicable over three summer months as opposed to the entire year.

## Availability of Demand Charges and Energy Differentials

The viability of customer-owned energy storage depends on realizing peak-shaving benefits with lower utility bills. Therefore, it requires either demand charges or energy differentials to be a component of the local utility's rate structure. LADWP rate A2-A, for example, has a $16.49/kW demand charge, but no energy differential. The demand charge is relatively high, which will make storage relatively attractive, but the customer's energy consumption (and energy charges) will *increase* due to losses in the charge/discharge cycle. Thus, the benefits of demand charge savings will be offset by increases in energy charges. In contrast some tariffs, such as AEP Ohio, incorporate high on-peak/off-peak differentials. AEP's rate GS-TOD has an on-peak energy charge of $0.072/kWh and an off-peak energy charge of $0.025/kWh. Because the on-peak charge is 288% of the off-peak charge, this more than offsets the system's round-trip energy efficiency[7]. For example, if the system's round-trip efficiency is 70%, then the dollar value of every kWh delivered will be 2.88 × 0.70—or 2.02 times the cost of charging. This rate schedule, however, provides no benefit for demand-charge reduction. In some cases, the tariffs have neither demand charges nor energy differentials (*e.g.,* AEP Texas' General Service rate). Storage would be of no benefit in PS applications when such tariffs are in use.

## Multiple Tariffs

Some utilities offer customers a choice of multiple tariffs. For example, FP&L offers three commercial tariffs: one based upon straight energy consumption (GS-1), one that includes a demand

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[7] Round-trip energy efficiency is the ratio of AC energy discharged to AC energy charged. The AC/DC power conversion losses, auxiliary loads, and other losses are all included.

charge (GSD-1), and one that includes both a demand charge and a TOU energy differential (GSDT-1). Of these, the most favorable tariff for storage would be the third because both demand charge and energy differential benefits would be realized. An FP&L customer with energy storage switching from the default GS-1 to GST-1 would realize the greatest utility bill savings. Care must be taken, however, to ensure that the storage system is sized properly and operates reliably; if the system is adequately sized to meet the full peak load, or if it does not operate when called upon, the customer will incur a demand charge of $8.16/kW that did not exist under the previous tariff.

# Applications: Peak Shaving & Power Quality

The NAS® BESS has been considered as a potential solution for a variety of large-scale consumer and utility energy storage applications. The present study considers a *combined* customer PS and PQ application. That is, the system assumed in the analysis is configured (as it was in Gahanna) for dual use.

In the PS application, the system uses its stored energy to discharge during periods of peak consumption, effectively 'shaving' the customer's peak load and reducing the peak demand as measured by the utility. As discussed above, in many commercial tariffs peak demand is charged monthly, so reducing peak demand provides direct savings on the customer's monthly utility bill. In other cases, the system may provide utility bill savings by using low-cost power from off-peak periods to displace high-cost power during peak periods. These benefits will be offset by the capital cost of the storage equipment and recurring maintenance and operating costs such as electricity used for charging.

In the PQ application, stored energy is used for back-up power during a utility disturbance (*e.g.,* a voltage sag or 'brown out') or outage. During such disruptions, the system disconnects the customer from the utility and functions as a UPS, directly serving the load. The PQ application provides value in terms of avoided productivity losses that would otherwise be encountered during the disturbance.

# Technical Considerations, Specifications, and Assumptions

## Ownership

The present analysis assumes that the NAS® BESS is installed on the customer's premises and electrically connected to the customer side of the meter. The customer is the owner-operator of the system, although a similar analysis could be performed under a leasing scenario or a third-party energy service scenario. For simplicity, only the customer ownership scenario is included here.

## Operating Regimes

As discussed above, the same NAS® battery may be configured for multiple operating regimes, each providing different combinations of PQ and PS availability. A set of selected operating regimes for a standard 50-kW NAS® battery module is shown in Table 12. Operating Regime A was provided by Technology Insights as a valid alternative to NGK's Operating Regimes 1 through 9. This regime was not an option in the Gahanna demonstration, but could be added to the modules' standard operating regimes with minor software changes. Operating Regime A is used for this economic assessment. The PQ Factor is the power multiplier for short-duration PQ events (*e.g.,* a PQ Factor of 5 indicates that the 50-kW module is capable of delivering 5 × 50 or 250 kW for the specified outage duration). As the table shows, trade-offs are made between outage duration, PQ Factor, available energy, and life-cycle. These trade-offs should be considered by the customer when selecting the operating regime.

**Table 12. Selected NAS Operating Regimes for 50-kW Modules**

| Operating Regime | Outage Duration | PQ Factor | PS Energy ($kWh_{ac}$) | PS Cycles Over Life |
|---|---|---|---|---|
| 1 | 30 sec | 5.0 | 0 | 0 |
| 3 | 30 sec | 3.0 | 155 | 2500 |
| 5 | 5 min | 4.5 | 0 | 0 |
| 6 | 5 min | 3.5 | 155 | 500 |
| 7 | 5 min | 3.5 | 360 | 500 |
| 8 | 15 min | 4.0 | 0 | 0 |
| 9 | 15 min | 3.7 | 155 | 500 |
| A | 30 sec | 3.0 | 360 | 2500 |

For PS operation, the available energy and cycle life are the relevant parameters. The higher the PS Energy rating, the more energy that can be bought off-peak and discharged during on-peak intervals. Or, if the customer's rate schedule included a demand charge, the stored energy could be used to serve loads during the customer's peak demand times and reduce the measured demand peak. With a high energy rating, fewer NAS® modules would be needed for the same energy requirement, thus saving capital costs.

For PQ operation, the combination of PQ Factor and Outage Duration determines the load protection capabilities of the system. A higher PQ Factor means that a larger load can be protected; a longer outage duration means that it will be protected for a longer period of time. These ratings, along with the customer's assessment of critical loads, define the number of NAS® modules and the capital investment required.

Finally, the service life of the NAS® battery as indicated by the number of PS charge/discharge cycles supported (PS Cycles over Life) is also a critical factor in the system's economic viability. With longer life, the benefits will accrue over more years and the frequency of module replacement will be lower, which reduces costs as well.

## Technical Specifications

A single-system configuration representing a medium to large electric customer was selected for the study. Although NAS® modules are available optimized for a single application, the module for this analysis was designed to provide dual PS and PQ operation. The system is capable of shaving a maximum of 250 kW with 1800 kWh of delivered, stored energy, which corresponds to a block dispatch of 250 kW for 7.2 hours, although the energy could be delivered at different power rates (*e.g.,* in a load-following control scheme). General specifications for the system assumed for this analysis are provided in Table 13. Additional technical specifications and assumptions are shown in Table 14, which is based on Operating Regime A in Table 12. Round-trip efficiency includes all double-pass PCS losses, battery losses, and auxiliary loads. O&M includes maintenance, standby heat losses, property taxes, and insurance.

**Table 13. System Specifications**

| | Module | System (5 Modules) |
|---|---:|---:|
| PS/PQ Power Rating | 50 kW/150 kW | 250 kW/750 kW |
| PQ duration | 30 seconds | 30 seconds |
| PS Energy | 360 kWh | 1800 kWh |
| Price[8] | $75,000 (module price) | $605,000 (installed) |

**Table 14. Technical Specifications and Assumptions**

| | |
|---|---:|
| PS Discharge Duration | 7.2 hours |
| Recharge Duration | 8.64 hours |
| Calendar Life | 15 years |
| Cycle Life | 2500 cycles |
| O&M | $26/kW-yr |
| AC/AC Round-trip Efficiency | 77% |

For this assessment a pulse factor of 3 was assumed. Pulse factors as high as 5 are possible, but not without adverse effects on battery life. A pulse factor of 3 provides a good level of PQ coverage without compromising the battery. Most outages are momentary, with durations not exceeding 30 seconds. For the specified pulse factor the system has a 30-second rating of 750 kW which could be used, for example, to cover critical facility loads up to 750 kW, even when the full facility load is higher. The critical loads would be isolated at the facility's service panel and the remaining non-critical loads would be connected on other circuits. PS operation would still be provided based upon the full facility load as measured at the utility meter.

## Tariff and Financial Assumptions

The economic assessment assumes that the NAS® battery described by the above technical specifications is installed at a customer site at which the 'typical' commercial tariff, shown in Table 15, is applicable. For simplicity, it is assumed to be an annual (non-seasonal) tariff that includes a (relatively typical) $10/kW demand charge. The tariff also assumes an on-peak energy charge of $0.08/kWh and off-peak energy charge of $0.06/kWh. While many tariffs provide greater on-peak/off-peak differentials, this two-cent spread is consistent with typical non-seasonal tariffs that include a demand charge. The facilities charge of $25 is also typical. While the NAS® BESS can be designed to provide reactive power support, kVAR charges are less common and are normally associated with larger, industrial customers.

The customer is assumed to have the load characteristics shown in Table 16 (prior to system installation). The customer has a peak demand of 1000 kW, and operates a straight shift during normal business hours. Financial assumptions are shown in Table 17. The discount rate of 7% is assumed to be the cost of a commercial loan for the customer.

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[8] Pricing and performance data was provided by Technology Insights and is based upon estimates (2006 pricing) for an installed system including modules, power conditioning ($202/kW), balance of system ($100/kW), land, shipping, and labor.

**Table 15. Tariff Assumptions**

| | |
|---|---|
| On-peak Demand Charge ($/kW-mo) | 10 |
| Facilities Charge ($/mo) | 25 |
| On-peak Energy Charge ($/kWh) | 0.08 |
| Off-peak Energy Charge ($/kWh) | 0.06 |

**Table 16. Customer Billing Data**

| | |
|---|---|
| Days in Billing Cycle | 30 |
| Peak (Operating) Days in Billing Cycle | 20 |
| On-peak Consumption (kWh) | 400,000 |
| Off-peak Consumption (kWh) | 100,000 |
| On-peak Demand (kW) | 1,000 |

**Table 17. Financial Assumptions**

| | |
|---|---|
| Escalation Rate | 2.50% |
| Discount Rate | 7% |
| State Marginal Tax Rate | 5% |
| Federal Marginal Tax Rate | 35% |
| Study Period (years) | 15 |

While the PS benefits are determined by the utility tariff, the PQ benefits are customer specific. The NAS® BESS would be able to protect loads from loss of power in the event of a utility disturbance or outage, provided that the period of the event does not exceed the assumed duration (30 seconds). By protecting the loads, the customer would be able to continue operating during the outage. Productivity is not lost, and losses (such as equipment failures) are avoided. The valuation of these avoided costs is site specific and the basis for this assessment is shown in Table 18. Thus, for protecting 750-kW of critical loads at $5/kW for 20 events per year, the specified system can realize a savings of $75,000 per year.

**Table 18. Assumed Outage Values and Frequency**[9]

| | |
|---|---|
| Value ($/kW-event) | 5 |
| Events per year | 20 |

# Results of the General Economic Analysis

## Bill Comparison

Based upon the technical and tariff assumptions shown above, the monthly utility bill may be calculated as shown in Table 19. The battery discharges on operating days (*i.e.,* business work days or 20 days per month) during peak hours, which decreases the on-peak consumption of utility power from the original 400,000 kWh to 364,000 kWh. The on-peak energy charges are correspondingly reduced from $32,000 to $29,120, for a monthly savings of $2,880. In contrast, off-peak energy use

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[9] James Eyer, Joseph Iannucci, and Garth Corey. SAND2004-6177. *Energy Storage Benefits & Market Analysis Handbook: A Study for the DOE Energy Storage Systems Program.* December 2004.

(for charging the battery and to overcome efficiency losses in the cycle) is increased. Off-peak energy use is increased from 100,000 kWh to 146,753 kWh, which increases the monthly bill by $2,805—an amount that almost completely offsets the on-peak savings. Consequently, the economic advantages to be realized from energy cost savings are negligible. Peak demand, however, is reduced from 1000 kW to 750 kW, which results in a monthly savings of $2,500 based on the assumed $10/kw demand charge. Consequently, the total monthly utility bill savings is $2,575 per month. Assuming that the system operates for eight months each year, the total annual savings will be $25,598.

**Table 19. Monthly Bill Comparison**

| | Without NAS® BESS | With NAS ® BESS | Benefit |
|---|---|---|---|
| On-peak Consumption (kWh) | 400,000 | 364,000 | |
| Off-peak Consumption (kWh) | 100,000 | 146,753 | |
| On-peak Demand (kW) | 1,000 | 750 | |
| Total Consumption (kWh) | 500,000 | 510,753 | |
| Load Factor | 0.694 | 0.946 | |
| | | | |
| Utility Bill ($) | | | |
| On-peak Demand Charge | 10,000 | 7,500 | 2,500 |
| Facilities Charge | 25 | 25 | 0 |
| On-peak Energy Charge | 32,000 | 29,120 | 2,880 |
| Off-peak Energy Charge | 6,000 | 8,805 | -2,805 |
| **Total Bill ($/month)** | **48,025** | **45,450** | **2,575** |
| | | | |
| PS Operating months/year | | | 8 |
| Annual Utility Bill Savings ($/year) | | | 20,598 |

## Proforma Analysis

The proforma analysis in Table 20 shows cash flows over a 15-year period. The table breaks down costs and benefits by application (PS and PQ), and includes all relevant cash flows. The affect of corporate income tax is calculated from these cash flows and depreciation under published Modified Accelerated Cost Recovery System (MACRS) depreciation schedules. Federal and state marginal tax rates are combined into a single marginal tax rate as follows:

$$EffectiveTaxRate = StateTaxRate + (1 - StateTaxRate) \times FedTaxRate$$

In the case study, the customer is assumed to have a state marginal tax rate of 7% and a federal marginal tax rate of 40%. These are combined using the above equation to give an effective tax rate of 44.2%. The net present value (NPV) of the after-tax cash flow is shown to be positive in the amount of $116,335, and the after tax internal rate of return (IRR) is 9.80%.

## Table 20. Proforma Analysis

|  | NPV | YEAR 0 | YEAR 1 | YEAR 2 | YEAR 3 | YEAR 4 | YEAR 5 | YEAR 6 | YEAR 7 | YEAR 8 | YEAR 9 | YEAR 10 | YEAR 11 | YEAR 12 | YEAR 13 | YEAR 14 | YEAR 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **NAS Ownership** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| NAS Capital Cost | **(604,500)** | (604,500) |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| NAS Depreciation |  |  | (30,225) | (57,428) | (51,685) | (46,547) | (41,892) | (37,660) | (35,666) | (35,666) | (35,726) | (35,666) | (35,726) | (35,666) | (35,726) | (35,666) | (35,726) |
| NAS O&M | **(68,621)** |  | (6,500) | (6,663) | (6,829) | (7,000) | (7,175) | (7,354) | (7,538) | (7,726) | (7,920) | (8,118) | (8,321) | (8,529) | (8,742) | (8,960) | (9,184) |
| **Power Quality** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| PQ Loss Savings | **791,783** |  | 75,000 | 76,875 | 78,797 | 80,767 | 82,786 | 84,856 | 86,977 | 89,151 | 91,380 | 93,665 | 96,006 | 98,406 | 100,867 | 103,388 | 105,973 |
| **Peak Shaving** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Utility Bill Savings | **217,460** |  | 20,598 | 21,113 | 21,641 | 22,182 | 22,737 | 23,305 | 23,888 | 24,485 | 25,097 | 25,725 | 26,368 | 27,027 | 27,703 | 28,395 | 29,105 |
| Net Profit/(Loss) Before Tax |  |  | 58,873 | 33,898 | 41,924 | 49,403 | 56,456 | 63,146 | 67,661 | 70,245 | 72,832 | 75,606 | 78,328 | 81,239 | 84,102 | 87,158 | 90,168 |
| LESS: Tax | **(219,787)** |  | (22,519) | (12,966) | (16,036) | (18,897) | (21,594) | (24,153) | (25,880) | (26,869) | (27,858) | (28,919) | (29,960) | (31,074) | (32,169) | (33,338) | (34,489) |
| Net Profit/(Loss) After Tax |  |  | 36,354 | 20,932 | 25,888 | 30,506 | 34,862 | 38,993 | 41,781 | 43,376 | 44,974 | 46,687 | 48,367 | 50,165 | 51,933 | 53,820 | 55,679 |
| ADDBACK: Depreciation |  |  | 30,225 | 57,428 | 51,685 | 46,547 | 41,892 | 37,660 | 35,666 | 35,666 | 35,726 | 35,666 | 35,726 | 35,666 | 35,726 | 35,666 | 35,726 |
| **NPV** | **116,335** | **(604,500)** | **66,579** | **78,360** | **77,573** | **77,053** | **76,754** | **76,653** | **77,446** | **79,042** | **80,700** | **82,352** | **84,093** | **85,831** | **87,659** | **89,485** | **91,405** |
| **IRR** | **9.80%** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| MACRS Depr Rate (15 year) |  |  | 5.00% | 9.50% | 8.55% | 7.70% | 6.93% | 6.23% | 5.90% | 5.90% | 5.91% | 5.90% | 5.91% | 5.90% | 5.91% | 5.90% | 5.91% |

## Economic Analysis Conclusions

The economic analysis shows a rate of return of 9.8%, which exceeds the 7% discount rate. Under the technical and economic assumptions described, the system represents an economically favorable investment because it provides a return greater than the cost of money. The present value of PQ benefits was estimated at $791,000, compared with PS benefits of $217,000. Thus, PQ benefits represent 78% of the total benefits, PS only 22%. PQ benefits are site specific, however, and finding places with high PQ payback requires knowledge of specific sectors and participants. While PS benefits are not as large, it would be relatively easy to find utilities that offer tariffs more favorable to PS operation than the 'typical' tariff assumed here. Overall, the results suggest that the dual application of the NAS® BESS does provide potentially attractive economics. The feasibility of specific projects, however, must use actual cost data, estimates of customer-specific avoided outage costs, and the actual terms of the local utility tariff.

# Multiple Technology Demonstration

## Introduction

Most electric utility customers consider periodic disruptions in their power service as inevitable nuisances, and are willing to operate within existing standards of reliability. Some customers however, are severely affected by disturbances. Manufacturers, data centers, and health care providers, for example, often require higher reliability than other customers, and invest in technologies that provide enhanced PQ protection.

Evaluating PQ problems at a given customer facility is complicated by the types of loads served, the location of the customer in the utility distribution system, and the costs to the customer. For example, some retail businesses are able to sustain short term (one or two second) outages without significant impact, but incur heavy sales losses during sustained outages. In contrast, some manufacturing customers suffer heavy losses from short term outages due to damaged equipment, but if they were given sufficient ‘bridging’ time to shut down their operations or to start a back-up generator, they could handle longer term outages without significant loss.

Three advanced ESS technologies, each capable of protecting customer loads during utility disturbances, were installed for evaluation at an AEP site in Gahanna (suburban Columbus), Ohio. These installations provided AEP the opportunity to gain familiarity with the operation of advanced PQ technologies, each as potential solutions that AEP could offer to commercial customers requiring enhanced reliability for critical loads. The technologies included the NGK NAS® BESS, the S&C PureWave lead-acid BESS, and the Active Power flywheel, all of which are shown in Figure 10. The three systems are fully integrated, including advanced energy storage technologies, power electronics, utility interface equipment, and monitoring and control capabilities. Each system was installed in compliance with standard commercial installation requirements. In all cases, the technologies represent designs that have since been replaced by more recent designs for the commercial market.


S&C PureWave Lead-acid System


ABB/NGK NAS® BESS

MGE UPS/ActivePower Flywheel

**Figure 10. Three technologies evaluated at AEP.**

## Scope

This study was not intended to consider all possible PQ solutions. It does not consider the full range of solutions that provide extended outage protection nor low-cost solutions that protect only against voltage sags (but not outages). It does not consider the range of commercial UPS products available on the market. Rather, the present study documents a selected group of technologies in various stages of commercial readiness at a specific location in the AEP distribution system. The study was done at AEP's request to evaluate PQ solutions for its customers. For the three technologies evaluated only the systems' responsiveness and ability to mitigate PQ events was evaluated. System performance and economics were not evaluated as part of this comparison.

Because the intent of this study was to document the ability of each system to respond to the same grid disturbances, rather than to evaluate and compare system performance, the three technologies were assigned random designations (A, B, and C) to maintain anonymity. While the technologies are not identified with the results, these designations are used consistently throughout the report.

## Demonstration Site

This comparison was performed to take advantage of a unique opportunity. Specifically, the three technologies to be evaluated were all located close to one another in a real commercial setting that shared the same utility distribution feeder. Sharing a feeder, they each encounter the same utility disturbances, including voltage sags and outages. Thus, the AEP site provides an opportunity to assess their individual responses to the same events. The systems served three similarly sized AEP office buildings as a test environment. While they were not installed on customer sites or on critical loads, the demonstration sites were fully instrumented to determine the systems' possible effects on loads in a commercial setting.

# Topologies

## Off-line Topology—Systems A and C

Systems A and C use on an off-line topology that is based on an insulated gate bipolar transistor (IGBT) based PCS. System A was designed to operate at its continuous rating, and System C was designed for short-duration, pulse-power dispatch. The off-line topology requires each system to detect a PQ event, inject full 3-phase power into the AC supply, and open a high-speed static switch to the utility (so as not to back-feed a fault). When the utility is restored, these systems resynchronize with the utility, close the static switch, and later recharge the energy storage devices. The benefit of an off-line topology is high efficiency under normal operating conditions (*i.e.,* when the system is not discharging) because the utility is directly supplying the load. The disadvantage is that the system must detect and respond to power disturbances in sub-cycle timing.

## Inline Topology—System B

System B uses an inline IGBT-based PCS designed to operate at its continuous rating. During normal operation, all power is routed through the power electronics to the load. The advantage of this topology is the complete separation of the customer from both voltage and frequency perturbations on the grid without any of the delays associated with detecting disturbances or transferring power sources. It is also a relatively simple control matter to continue drawing full power from any remaining grid phases to support the storage device supplying 3-phase power to the customer. The disadvantages are a full reliance on the reliability of the PCS and the cost of approximately 5% PCS inefficiencies associated with the continuous rectification/inversion of power.

# Data Collection

## Data channels

Waveform event data was collected by AEP technicians. The systems were monitored independently (no cross-triggering) using Dranetz/BMI 3-phase Power Platform PP1 power quality data-loggers. Each data-logger was capable of collecting voltage and current data at four locations. For each technology, three load phases and one grid phase was monitored (see Figure 11). As shown in the figure, grid monitoring for Systems A and C was from A-phase, and grid monitoring for System B was from B-phase. For each event, the data-logger stored one cycle of pre-trigger data, the event itself, and one cycle of post-event data. Trigger points were set to ±10% root mean square (RMS) voltage and source current below 10 A. Event data was stored in the data-logger using a proprietary format and downloaded periodically from the field. Data was then analyzed using the Dranetz/BMI Dran-View software package.

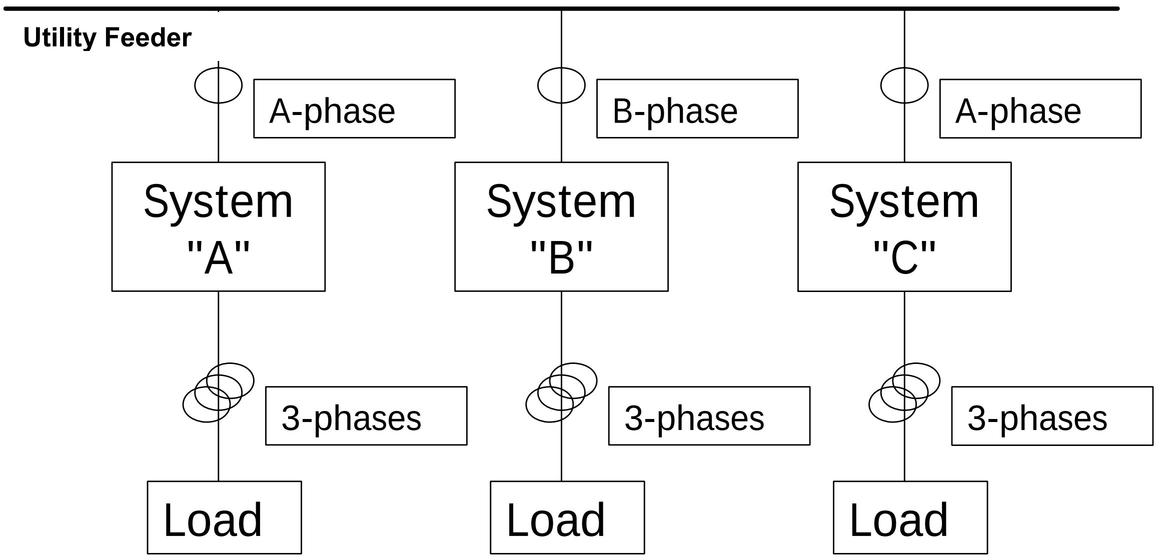

**Figure 11. Monitored voltages on a common AEP feeder.**

## Study Periods

Synchronized and intensive data collection was performed for the three technologies over a period of six months between October 2003 and April 2004. Due to the trial nature of the projects data-monitoring equipment was frequently off-line at individual sites, which limited the amount of synchronized data available. Nevertheless 14 periods of extended synchronized data were collected and captured a single-phase outage lasting more than one second as well as a rapid succession of eight voltage sags. These two events propagated through all three systems; the events are described in more detail below as are the individual system responses.

# System Response Results

## Single-phase Interruption

At 9:40 a.m. on October 29, 2003, there was a 100% A-phase grid voltage failure for a period of 68 cycles (1.133 seconds). This failure propagated throughout the distribution area containing the three demonstration systems. The three sites monitored slight variations in the voltage drop at the onset of the interruption, which is most likely a function of their interconnection topologies. The durations of the interruption as well as the voltage rise after a period of 1.133 seconds were similar.

For System A, the A-, B-, and C-phase load-side voltages before the interruption were 288 V, 281 V, and 283 V, respectively. On the loss of A-phase the system activated and supported the load, allowing only a 6%, 4-cycle, A-phase sag through. This is well within industry standards for acceptable power quality. B- and C-phase were regulated to 277 V, the nominal customer voltage. Figure 12 shows the described event, including the A-phase grid-side voltage and the three load-side voltage phases (A, B, and C). The load saw a brief drop in A-phase voltage and a slight overcompensation in all three phases during the transition from the utility source to the technology source.

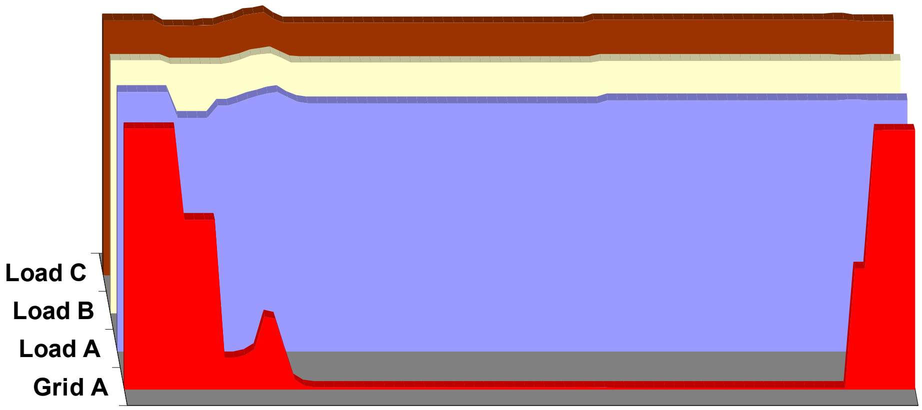

Figure 12. System A response to 68-cycle A-phase interruption.

The response of System B is shown in Figure 13. This figure shows the B-phase grid-side voltage, but it is the same event depicted in Figure 12 which shows the A-phase grid-side voltage. Upon the loss of utility voltage, the system continued to support the customer with no apparent voltage perturbations. Load-side voltages remained at a steady 277 V, 275 V, and 276 V, respectively throughout the interruption.

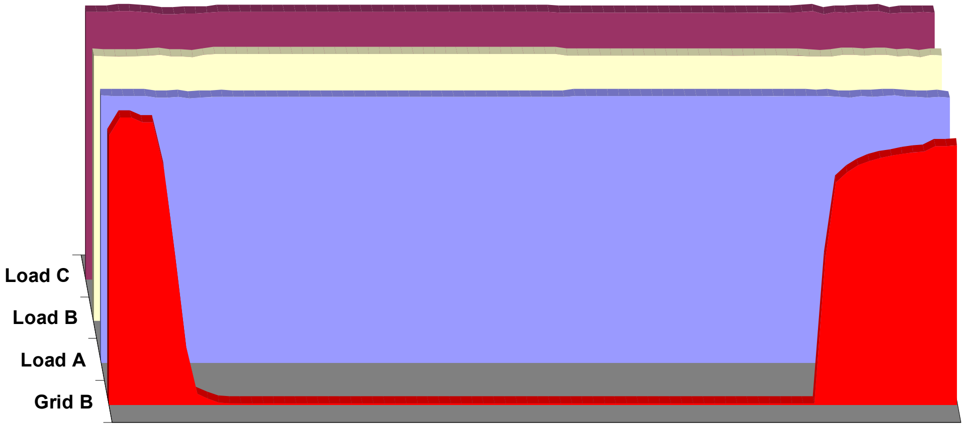

Figure 13. System B response to 68-cycle A-phase interruption.

For System C, the A-, B-, and C-phase load-side voltages before the interruption were 287 V, 277 V, and 277 V, respectively. On the loss of A-phase, the system detected the disturbance, activated, and supported the customer with no loss of load. Nevertheless, the disturbance did result in a two-cycle, 34% sag on the A-phase load-side voltage. The B-phase load-side voltage had a three-cycle 7% sag, and C-phase had a three-cycle voltage increase to 308 V (111% of nominal). These events are shown in Figure 14.

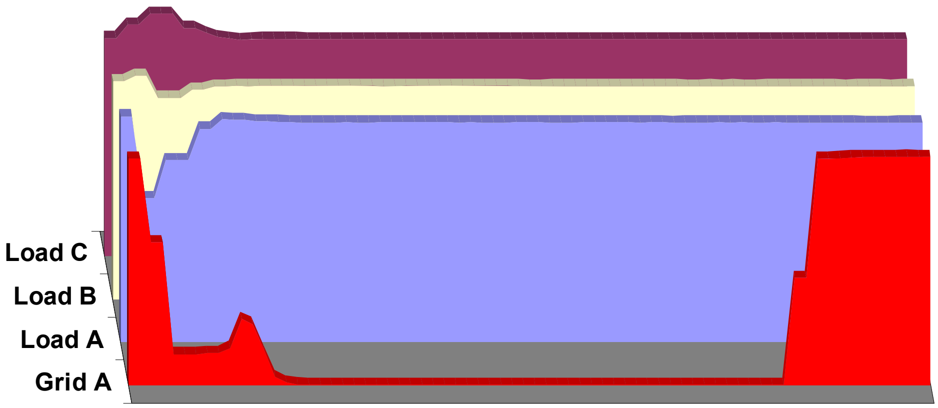

Figure 14. System C response to 68-cycle A-phase interruption.

To assess the magnitude of these load-voltage variations, the events are plotted in Figure 15 against an accepted industry standard of PQ tolerance (the 1996 ITIC curve). As shown, the A-phase load-side voltage fell just outside of this tolerance. However, none of the loads supported by System C were negatively affected.

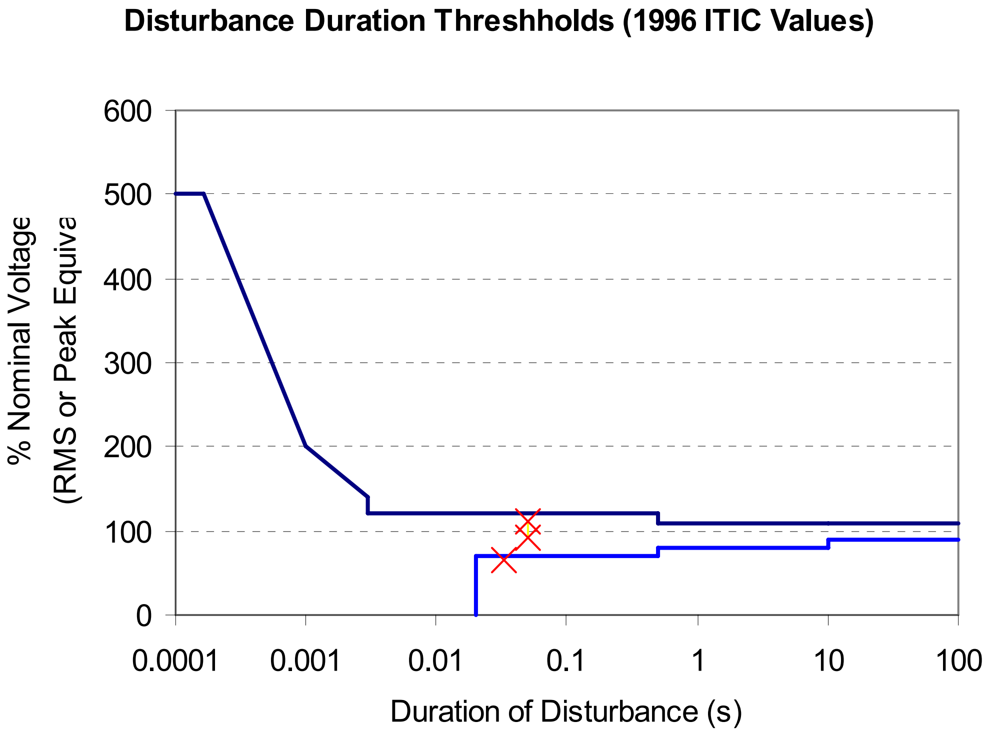

Figure 15. Industry standard for acceptable power quality.

## 3-phase Repetitive Sags

On November 28, 2003, at 10:05 a.m., a sequence of 22% sags on the A-phase grid-side voltage was observed. The sequence included four double-sag events over a four-hour period for a total of eight sags. The individual sags lasted up to six cycles. Figure 16 shows the timing and characteristics of these sags. The sags propagated throughout the distribution area containing the three demonstration systems. Each of the systems responded appropriately and protected their respective customers from penetration of all eight sags. Figure 17, Figure 18, and Figure 19 show the systems' responses to the last of the eight sags, occurring at 2:03 p.m.

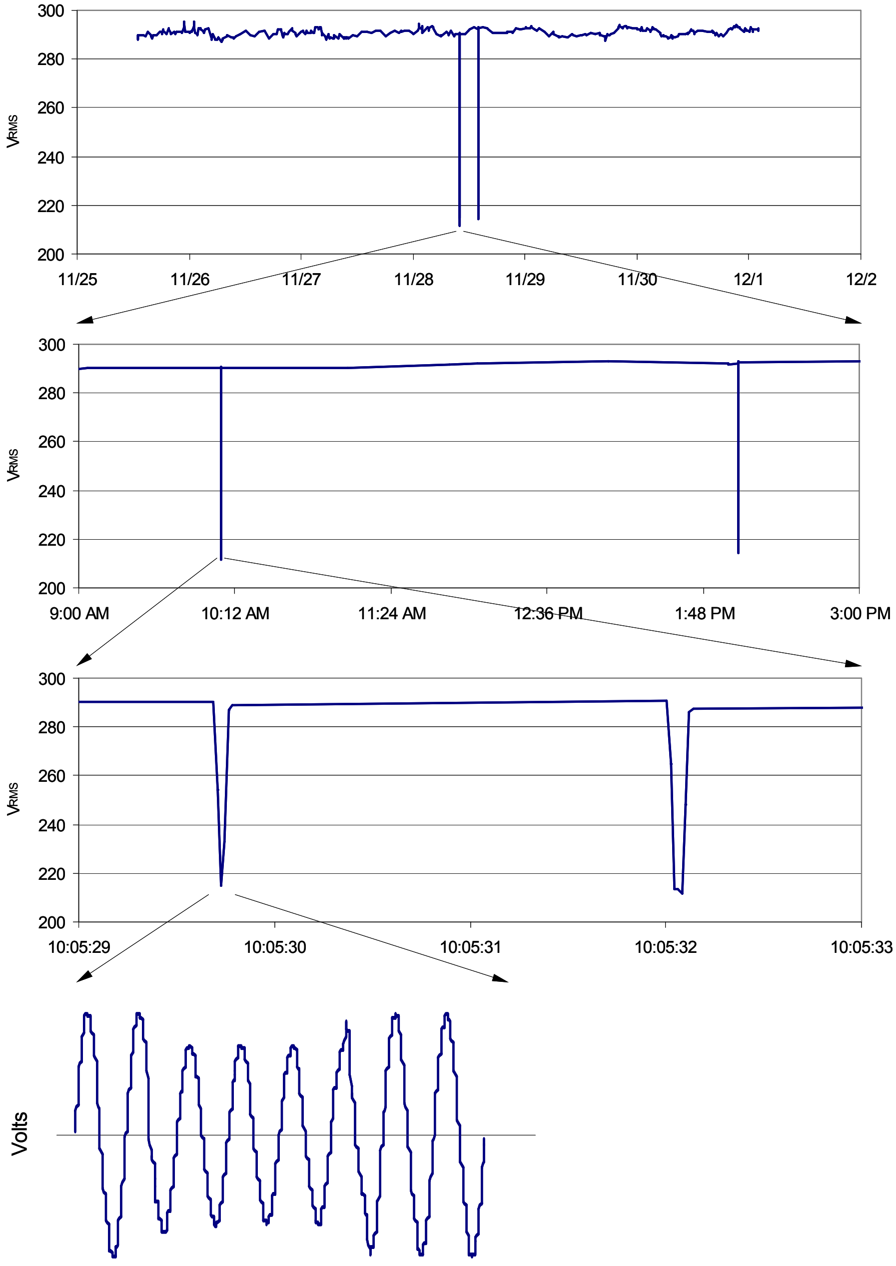

**Figure 16. Eight sag events over a four-hour period on November 28, 2003.**

For System A, the A-, B-, and C-phase load-side voltages before to the interruption were 291 V, 284 V, and 285 V, respectively. During the A-phase sag event, the system activated and supported the loads above the 277-V nominal utility supply as shown in Figure 17. The voltage overcompensation, peaking at 9% over the following 8 cycles, was well within the 30-cycle, 20% industry tolerance illustrated in Figure 15.

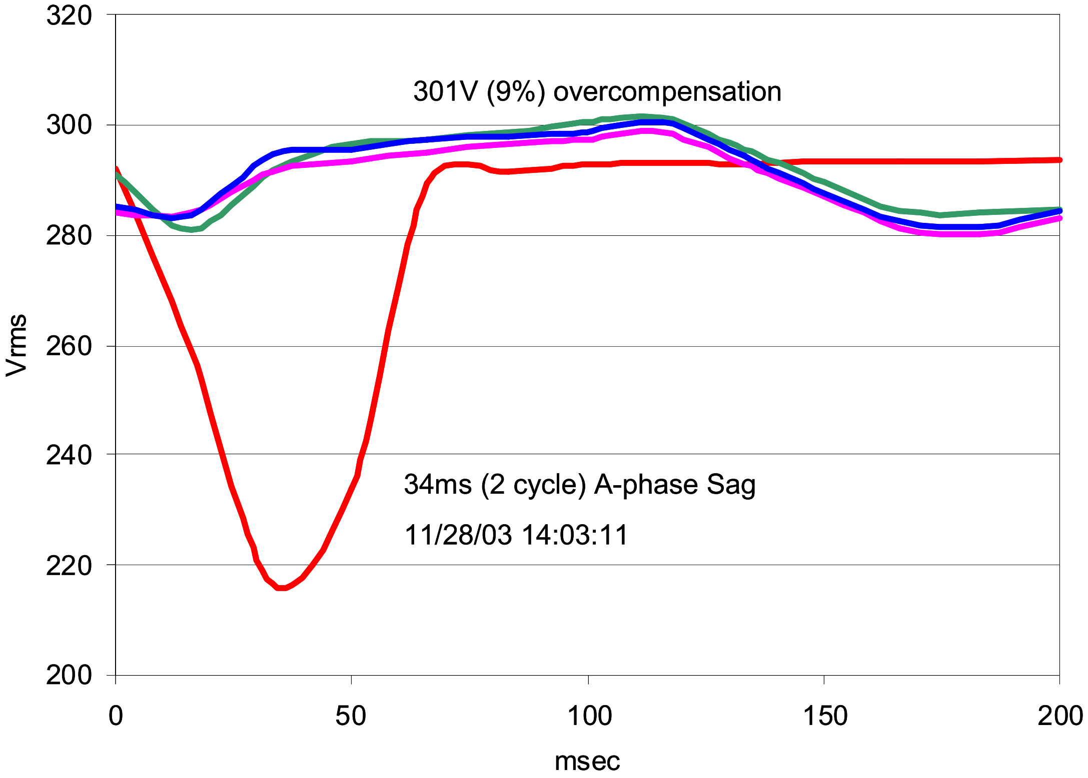

**Figure 17. System A sag response.**

For System B, the A-, B-, and C-phase load-side voltages before the interruption were 281 V, 275 V, and 277 V, respectively. During the sag event, the system activated and isolated the loads from any apparent impact by injecting a significant amount of current from its energy reserves. The response is shown in Figure 18.

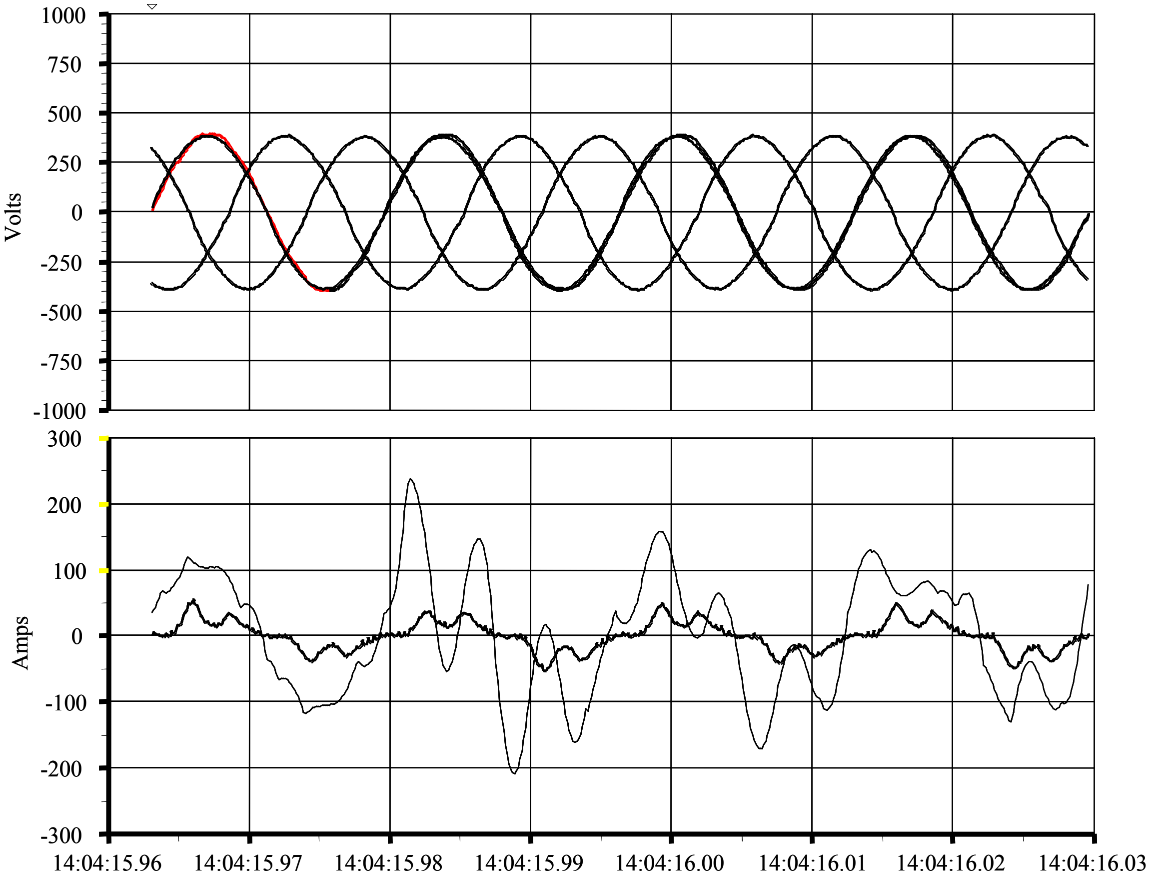

**Figure 18. System B sag response.**

## System C Response

System C transferred the load to its ESS within half a cycle and sustained supply voltages within industry tolerances. Figure 19 shows the A-phase load-side voltages through the duration of the sag event and the current supplied by the ESS.

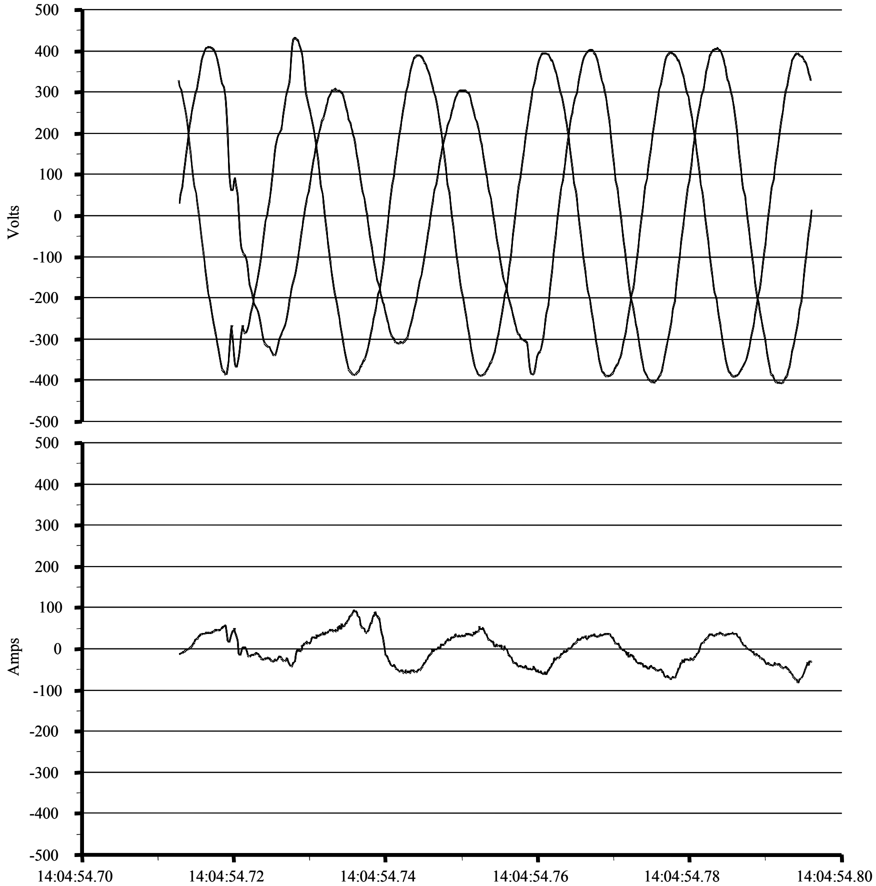

**Figure 19. System C sag response.**

# Multiple Technology Comparison Conclusions

Three PQ devices representing two PCS topologies and three energy storage technologies were tested on a common feeder at an AEP test site. During the data collection period, one 68-cycle interruption and eight voltage sag events were observed. One of these events was analyzed in detail. During the interruption all systems continued to support the loads without an outage. Systems A and B fully protected loads within 1996 ITIC-defined tolerances. System C fully protected the loads on two phases, but had a brief transition outside the tolerances on one phase. In all cases, the loads suffered no adverse effects. During the voltage sag event, all three systems fully protected the load. The results were consistent with the inline and off-line topologies for the three systems. Inline systems provide seamless transition at the cost of on-going throughput losses, while off-line systems require a load transfer but operate more efficiently during normal operation.

# Appendix A – Cycle Data Summary

The summary data presented below is based on various measures of interest defined for complete operational cycles, so each plotted point corresponds to one cycle. As discussed above, the NGK BMS provides ‘cycle numbers’ for each data record for each battery. The ‘cycle numbers’ for the batteries do not stay in synch, however, because individual batteries were exposed to unequal numbers of discharge cycles during testing. To support cycle-based analysis for the system as a whole, and to minimize the number of incomplete round trips, the ‘system cycle number’ is used for most of the summaries below.

## Battery Data

When reviewing NGK battery data, it is important to be aware that at various intervals the BMS provided no data. Additionally, the data includes information from the factory testing (at ABB) performed before the system was installed at the Gahanna demonstration site. Figure 20 and Figure 21 show the duration of each system cycle, but show the distinct data availability for the two batteries separately. The duration of each system cycle varies from one-day cycles Monday through Thursday, with three-day cycles typical for Friday through Sunday night. Some very short cycles occur when PQ discharges happen during the overcharge period.

The record shows gaps in data between July 1, 2002 and August 15, 2002 and at four subsequent times (11/12/02, 3/7/03, 5/2/03, and 5/24/03) the data was significantly less than complete. In November (12-18) 2003, ABB upgraded the PCS software. In March 2004 the system experienced a failure and repairs presumably required the BMS to be shut down. In the beginning of May 2004, the inverter and the battery experienced a communication hardware failure. In late July 2004, a grid-voltage imbalance began triggering superfluous PQ discharges that slightly disturbed the SOC values during the overcharge period, causing frequent very short ‘cycles’ to be detected by the ‘system cycle’ detection algorithm.

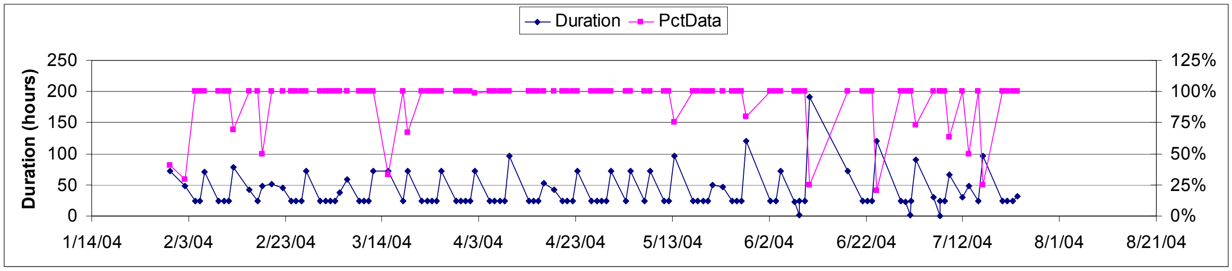

Figure 20. System-cycle duration and Battery 1 BMS data availability.

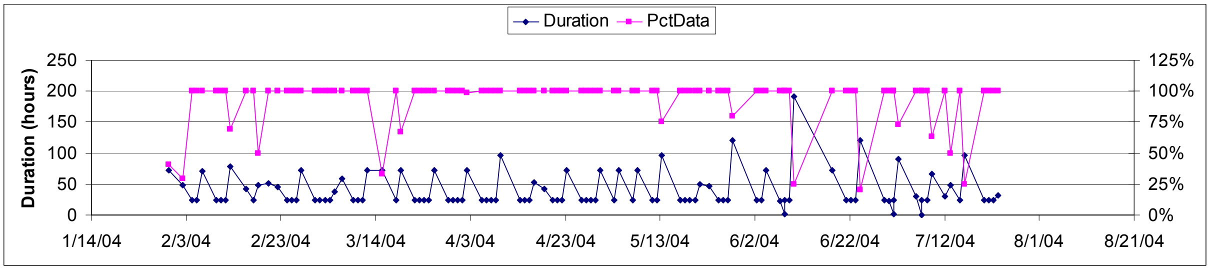

Figure 21. System cycle duration and Battery 2 BMS data availability.

In Figure 22 and Figure 23, the NGK 'cycle' numbers are plotted versus time. These cycle numbers usually increment together, but not always. The unified system PS cycles are shown in Figure 24 and are much lower than the full cycle counts in Figures 11 and 12. The data points shown in the remaining plots in this appendix are aggregates corresponding to these PS cycles.

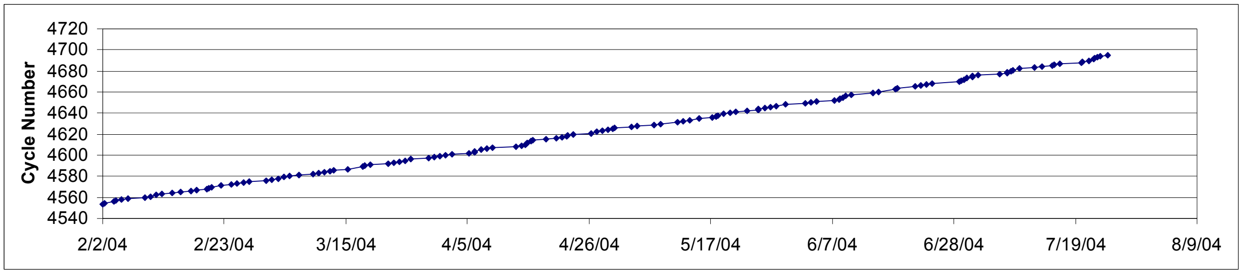

**Figure 22. Battery 1 cycle numbers.**

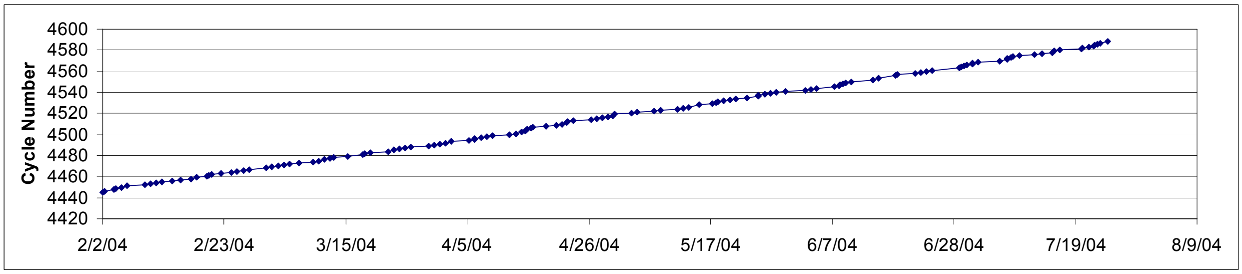

**Figure 23. Battery 2 cycle numbers.**

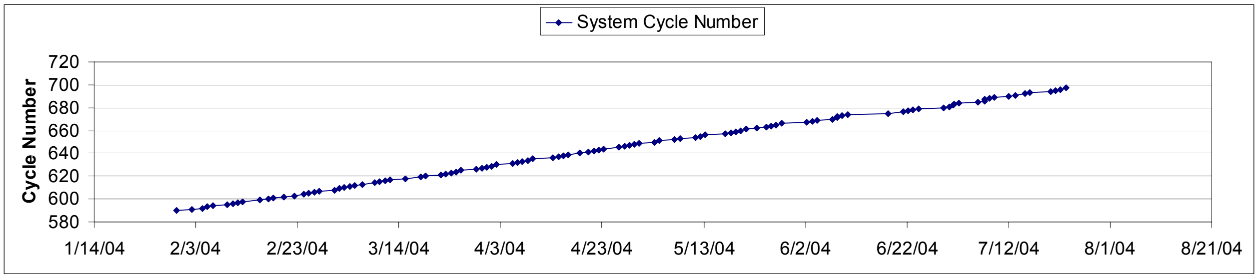

**Figure 24. System cycle numbers.**

In Figure 25 and Figure 26, the maximum DOD (as defined by the NGK controllers) per system cycle is shown for each battery. Battery 2 was reaching nearly 100% DOD during the first two weeks of March because the charge profile starting at 7:00 p.m. was not completing before the 5:55 a.m.[10] internal deadline for charge completion, so the batteries were drifting toward charge deficit. Charging was shifted to 6:05 p.m. on March 15, 2004 to allow longer charge duration and the discharge power level was reduced to give the batteries a chance to 'catch up'. The discharge power level was restored to 75 kW in early May and the charge start time was restored in mid-May with no apparent ill effects.

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[10] The ABB controller did not support automatic daylight savings time adjustments. The BESS must be manually shut down and reset to change the clock time. Because the 5:55 a.m. charge stop time was not adjustable, the battery clock had to be reset to align the discharge start time with the actual load. AEP reset the battery clock on June 16, 2004.

Figure 27 through Figure 30 present the temperature variation profiles for the batteries.

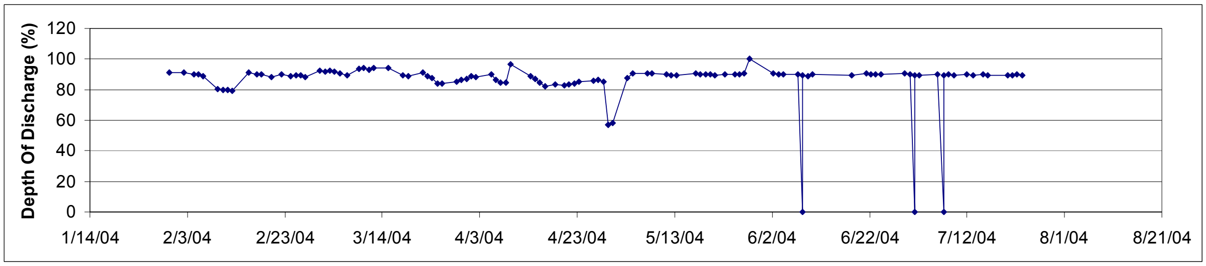

**Figure 25. Battery 1 maximum discharge level.**

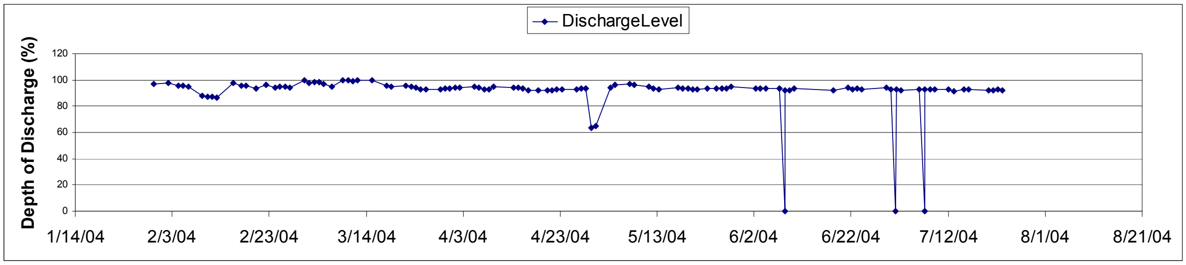

**Figure 26. Battery 2 maximum discharge level.**

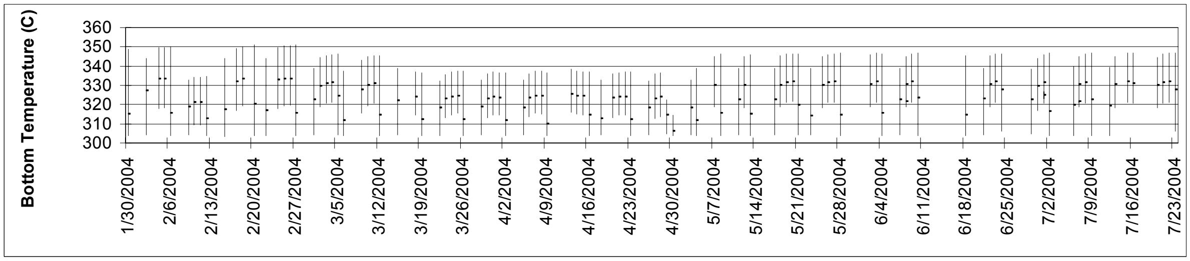

**Figure 27. Battery 1 bottom temperature variation.**

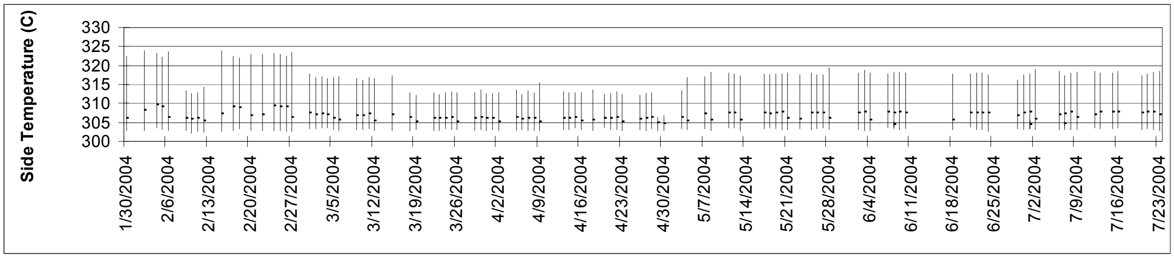

**Figure 28. Battery 1 side temperature variation.**

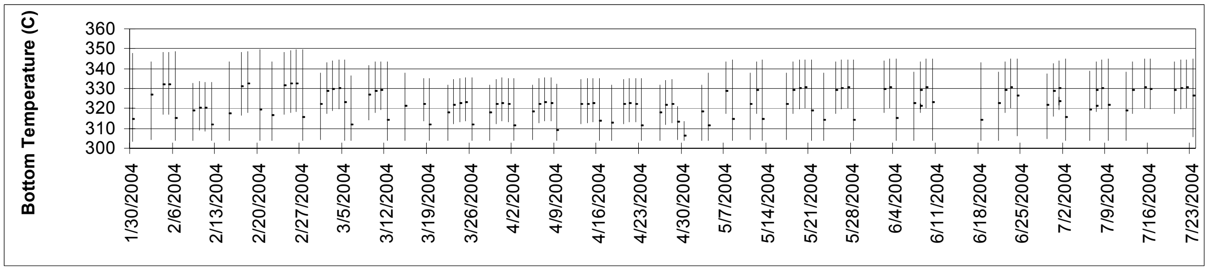

**Figure 29. Battery 2 bottom temperature variation.**

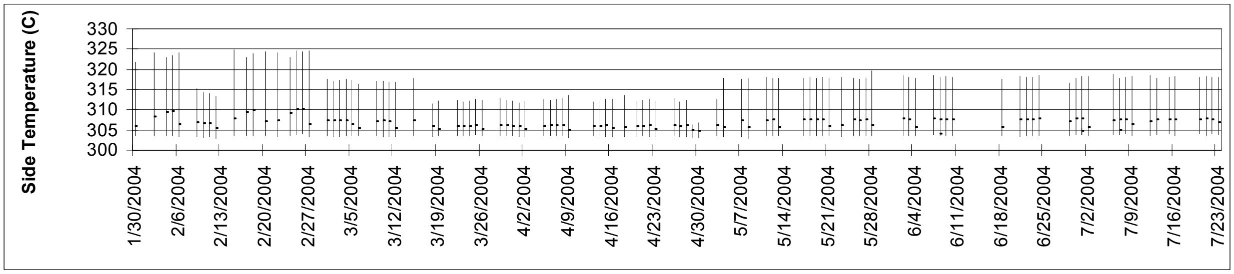

**Figure 30. Battery 2 side temperature variation.**

# System Performance

Figure 31 shows the duration of each system cycle with the available data available from all three kV2 meters summarized for each cycle. As shown in the figure, the duration of the system cycles is generally longer than the battery charging cycles shown in Figure 20 and Figure 21. Most of the 72-hour cycles are weekend non-discharge periods. The 3-day and 8-day cycles beginning March 15, 2004 and June 10, 2004, respectively are artifacts caused by missing DC data that was necessary to identify 100% SOC.

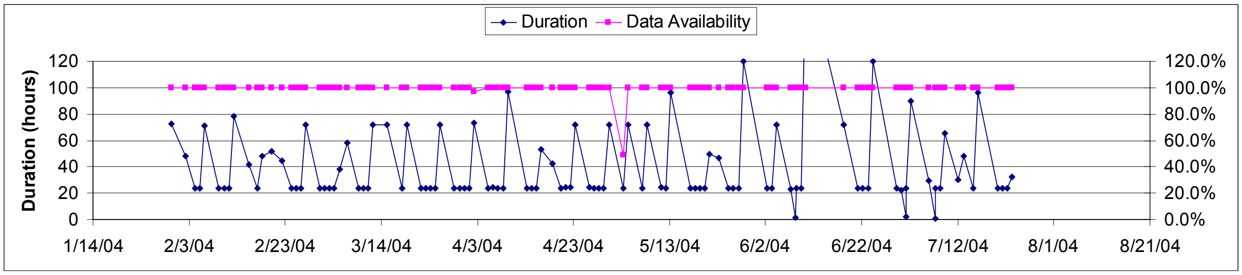

**Figure 31. System cycle duration and data availability.**

Figure 32 shows the energy used to charge the NAS® BESS, the energy received from the BESS during discharges, and the energy delivered to the NAS® BESS auxiliary load. The auxiliary load rises visibly when the device floats for extended periods of time, as the internal resistive losses no longer help keep the battery warm. The NAS® BESS cycles energy in a fairly predictable manner. The long cycles with large energy transfers are artifacts of missing data. Figure 33 re-formulates the information presented in Figure 32 as the system's round-trip efficiency.

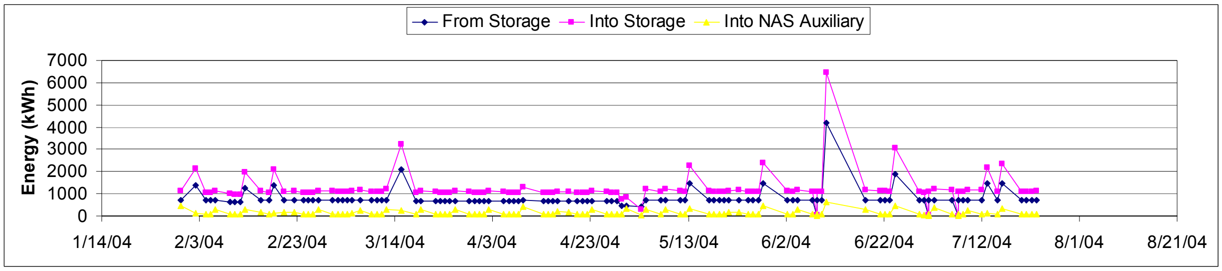

Figure 32. System energy charge and discharge.

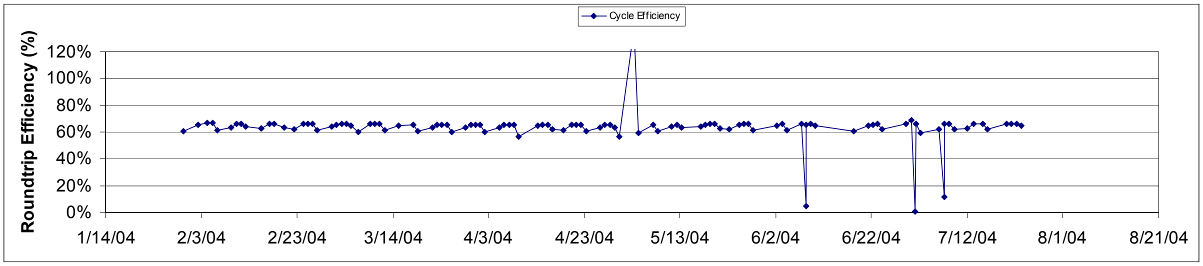

Figure 33. System charging efficiency.

Figure 34 shows the maximum one-minute-average power levels for the NAS® BESS. Figure 35 shows the maximum one-minute-average power levels drawn from the utility and supplied to the load over the course of each system cycle. The general trend apparent in this figure is that the maximum power drawn from the utility is always larger than the load. What is not apparent in this plot is that the maximum utility power draw occurs at night, while the maximum load power draw occurs in the daytime.

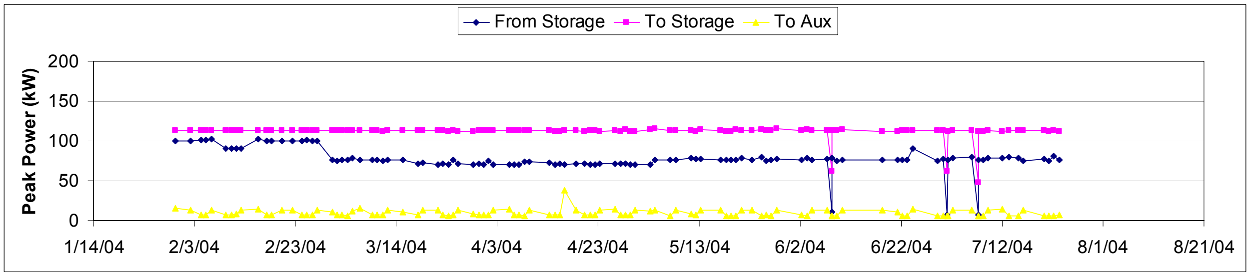

Figure 34. System peak power levels.

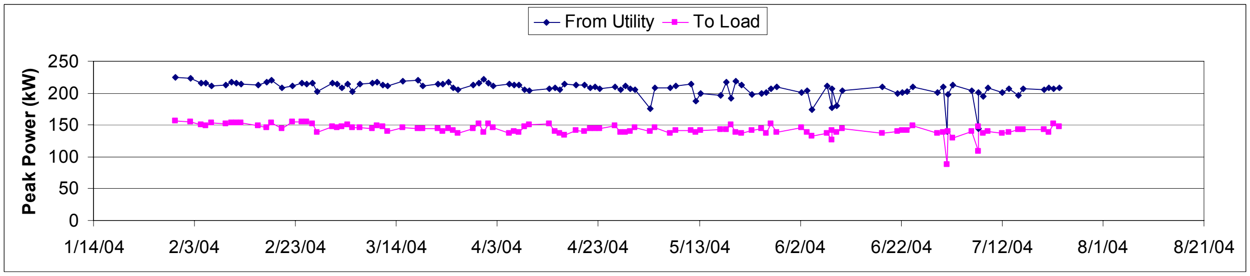

Figure 35. Installation peak power levels.

# Appendix B – DC Data Accuracy

## Background

In January 2004, AEP calibrated the NGK DC current sensors, along with proposed non-intrusive current sensors based on hall-effect technology. A review of this calibration data led to the conclusion that the DC current data did not have sufficient accuracy for use in this assessment. Additionally, NGK indicated that the battery's lower temperature limit was not correctly adjusted for the application, and that the resulting operating data would not reflect optimum performance. The battery was re-adjusted in the last week of January and configured to operate in Regime 6. The analysis, therefore, focused on data from the beginning of February 2004 to avoid the lower-temperature-limit-related problems; DC data (in particular accumulated quantities) was de-emphasized.

## Analysis

Uncertainty is apparent in both the independent calibration of the current measurements, and in the recorded data. The calibration performed by AEP consisted of connecting a hall-effect current sensor (manufactured by LEM) and a current shunt in series with the NGK DC current sensors, for each of the two batteries in the NAS® BESS; a DC power supply was used to control current level through the series sensors. The DC shunt was treated as the reference. The test sequence took readings at zero current, then increased current in steps, then reset to zero, and decreased current in steps (toward more negative values).

The first point of concern with the calibration data appeared in the initial zero reading, in which the NGK data for Battery 1 was -1.5 A except for one reading which was -1 A. This abnormal stability in the readings suggests that a significant quantizing (rounding-off) effect could be occurring. Battery 2 yielded values of either 0.4 or 0.9 A, with no intermediate values, again suggesting the possibility that significant quantizing was occurring.

The second point of concern was that after a linear regression was performed to identify a relationship between the NGK and shunt measurements, the residuals (the difference between measured and predicted values) for Battery 2 (see Figure 36) suggest that there may be a different slope for the negative currents than the positive currents (which is evidenced by the nonzero residual at zero current). The calibration coefficients are shown in Table 21.

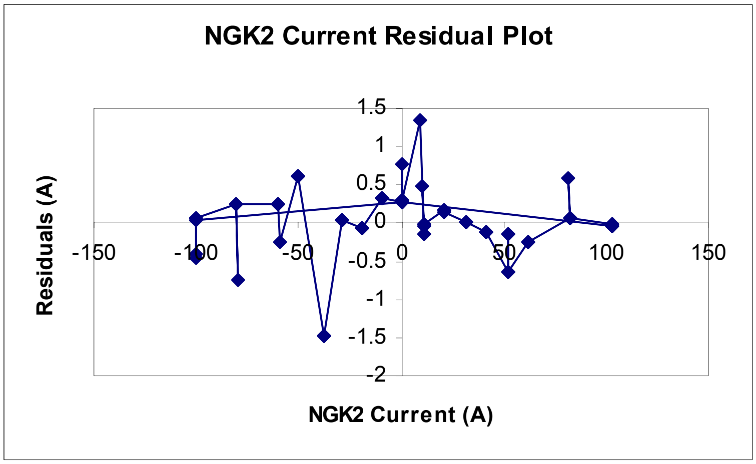

**Figure 36. Linear regression residuals for Battery 2 current.**

**Table 21. Calibration Coefficients**

| | LEM1 | LEM2 | NGK1 | NGK2 |
|---|---|---|---|---|
| Offset | 0.636169 | 0.0365013 | -1.528659 | 1.1928974 |
| Slope | 0.9947205 | 0.9843277 | 1.0004678 | 0.9836428 |
| Std Error | 0.0747875 | 0.1243587 | 0.3973615 | 0.4830779 |

A common rule of thumb for identifying the uncertainty for normally distributed errors is to double the standard error (95% confidence interval). That is, if the NGK errors were normally distributed, the NGK readings could be expected to be within ±0.8 A and ±1.0 A for the two batteries. Nevertheless, these uncertainties are significant when compared to the offset. The improvement offered by including the offset is difficult to distinguish from the random errors. Also, the apparent quantization mentioned above suggests that the errors may not be normally distributed. The third point of concern is that there was no indication in the residuals that errors are proportional to the magnitude, so relative errors at current readings that are small relative to the full scale (determined by peak expected values) will be significant. This was a key point that was not apparent in the original error specification, which when interpreted this way should be regarded as 1000 A × 0.5% = 5 A typical uncertainty.

## Data Accuracy Conclusion

Given the uncertainty of the calibration and the apparent sensitivity of the calculation to small differences in offsets, there is no method or coefficient for correcting the NGK DC current data to provide accurate results. In fact, there does not appear to be a way to identify an upper bound for the uncertainty of computed DC charge or energy quantities based on the NGK current measurements.

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