

Data Management for Fielded Energy Storage Systems

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ABSTRACT

In FY98, Sandia National Laboratories initiated a project to develop a comprehensive Data Base for stationary fielded battery energy storage systems for off-grid stand-alone and grid-tied systems. The purpose of the Data Base is to provide information to end users and system integrators on the operation and management of fielded battery energy storage systems in order to provide guidance in the design of future systems to avoid problems currently identified in fielded systems. The Data Base and subsequent analysis products are intended to provide practical field experience, information, and analyses to systems integrators and battery users. This paper reports on the efforts in the development of four similar and compatible Data Bases for four different fielded systems, with each containing the data from their unique collection and analytical efforts. The paper also describes each of the sites and the procedures used to evaluate the data collected at the various locations and concludes with the lessons learned from each of the project contractors.

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INTRODUCTION

Many sites were identified as candidates for the data management project for both grid-tied and off-grid systems. The primary driving force for site selection was the expected quality of data that would be available. The first task was to identify grid-tied and off-grid sites that would provide historical data for a battery energy storage system (BESS) that met the criteria for the analytical tasks previously identified to be of general interest to the industry. Consequently, four field sites, two grid-tied and two off-grid sites, were selected for the initial phase of the project. The first grid-tied site is located in Metlakatla, Alaska. The BESS functions as a regulation device for a small, island utility. The second grid-tied site is located in Homerville, Georgia. The BESS functions as a ride-through, power quality device that supports a 1 MW load for up to 10 seconds. The first off-grid site is located in Grasmere, Idaho. The BESS functions as a complete power plant that supports a remote Air Force radar site. The second off-grid site is in Wawona Point, Yosemite National Park, California. The BESS functions as a backup power source for a remote communications site.

Follow-on tasks involved the acquisition of data generated by the site data acquisition systems (DAS), evaluation of data quality and reliability, development of a Microsoft Access Data Base for the gathered data, and the design and development of analytical tools to perform initial analyses of the system to determine the history of battery use and identify systemic shortcomings in battery management. Secondary tasks were also defined to determine the adequacy of the DAS used for the fielded systems, to determine the adequacy of the battery management strategy applied to the fielded system, and to make recommendations for ways to increase the reliability of data acquisition systems for future systems. Because of the diversity of fielded systems, both off-grid and grid-tied applications were selected with the initial intent develop a common data base for all battery storage applications to assist in future data review and analysis. Although the four applications selected for analysis were very different from each other, it was anticipated that, with careful data gathering and analysis, all data would ultimately reside in a single Data Base.

DATABASE DESIGN CONSIDERATIONS

To develop the initial Data Base structure, a data kernel was defined that logically applied to all stationary battery applications. The kernel consists of the following eight time-referenced parameters and two non-time-referenced parameters:

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- Ah lifetime accumulation,
- Wh (AC and DC) lifetime accumulation,
- State-of-Charge,
- System DC Voltage,
- Overcharge (%),
- System power,
- DC Current,
- Battery Temperature..
- Also included in the kernel but not time-referenced are the following two parameters:
 - a. Duty cycle count,
 - b. Failures/Problems.

The database kernel is identical for all systems evaluated. Because of the diversity of the systems being analyzed, it was also anticipated that unique, although not initially known or defined, specifics for each individual system would also need to be included in the Data Base; however, each unique sub-database would connect only to the specific system database to which they related. Each of the four data bases included the kernel and also fully supported each individual system with an eye to the integration with the three other systems into a common data structure with common analytical tools.

CONSOLIDATING THE DATA BASES

Several meetings were held in the course of the project. Although there were significant similarities between the analysis of each of the systems, there were enough differences that would result in the loss of information for each system. The kernel accounts for much of the electrical performance data, the system performance data needed to be included in order to fully understand the functionality of the BESS and to evaluate its overall performance based on the application it was supporting. The main difference is in the use of the BESS for energy vs. power applications.

Final analysis indicated that the integration of energy and power applications into the same analytical Data Base was not appropriate. Because the primary failure mechanism for power applications is calendar time and the primary failure mechanism for energy applications is energy exchange, the correlation between the two systems is quite vague. Forcing each application into the same analytical environment results in a comparison of apples and oranges against a common criteria. Consequently, the results would be meaningless. As a result of the initial study, it was determined that, at a minimum, unique analysis techniques and perhaps unique Data Bases, needed to be developed to properly serve the purposes of each application.

Part of the final work performed was to complete an economic analysis of each system to determine the cost effectiveness of the BESS solution. That information and more details of the study by each of the four contractors will be available in SAND Report form by mid-year, 2001. Access to the final report can be found at www.sandia.gov/pstg and look in the publications area at the power sources technology group (pstg) web site. It is also anticipated that BESS information generated by the project and future analyses will also be available at the pstg web site.

FIELDDED ENERGY STORAGE SYSTEM SITES

Metlakatla

In February 1997, the (BESS) was commissioned by Metlakatla Power & Light (MP&L) for the purpose of stabilizing its electrical grid and reducing its dependence on costly diesel generation.

MP&L is a small stand-alone electric utility located on Annette Island in Southeast Alaska. Its generation assets include four hydroelectric units, which together produce 5 MW, and a 3.3 MW diesel unit. Peak load on the utility system varies from about 1.8 MW in the summer to 4 MW in the winter.

MP&L serves a small community primarily engaged in fishing and logging with approximately 800 residential customers and a few commercial customers. The largest industrial customer was the Annette Hemlock Mill, which

was the principal source of power disturbances for the utility. Disturbances were caused by the mill's two 600 hp induction motors used for sawing and chipping logs.

While the four hydro units were generally able to meet the total utility load requirements, they were too slow to respond to the fluctuating loads of the mill. Consequently, the diesel generator was installed in 1987 and used for load-following duty.

Even with the diesel generator, however, system stability continued to be a problem. Frequency excursions on the order of 1.0 Hz were common, and occasionally reached 2.0 Hz. Voltage fluctuations were not as severe, however sags and swells above 7.5% for one second were occasionally seen.

Furthermore, the operating costs of the diesel were high. About 450,000 gallons of diesel fuel were consumed each year. Fuel had to be transported by barge to the island and pumped from the shoreline to on-site storage tanks. Four employees were required to operate and maintain the engine-generator.

The BESS was designed to displace the operation of the diesel generator entirely. The BESS includes a single series string of GNB Absolyte IIP valve regulated lead-acid (VRLA) cells, a twelve-pulse GTO converter, two step-up transformers, four medium-voltage harmonic filters, and a control system. The BESS was installed as a joint effort between GE, GNB, SNL, and MP&L. By controlling the BESS to charge and discharge in response to load swings, the system frequency could be maintained at much tighter tolerances while giving adequate time for the hydro units to react. The battery would be kept at about 90% state-of-charge (SOC) to provide capacity to either absorb or generate real power to the grid. From this state, about 1.3 MWh could be utilized as reserve power in the event that one of the hydro units were to trip offline unexpectedly. In addition to generating or absorbing real power, the BESS was designed to provide voltage support by either sourcing or sinking reactive power.

An economic analysis was performed using actual cost data and conventional planning practices. Key economic impacts include the following:

- **Load Following.** The BESS provides load following service, nearly eliminating the operation of the diesel generator set. This saves about 450,000 gallons of fuel and reduces the net staffing requirements by 3.75 "full time equivalent" technical positions.
- **Reserve Generation Capacity.** The BESS defers the need for additional reserve peaking power throughout the battery design life of 10 years.
- **Voltage Regulation.** The BESS defers investment in two 450 kVAR switched capacitor banks.
- **Customer Claims.** The BESS reduces voltage transients on the distribution lines, saving costs of damaged customer equipment.

Results of the economic analysis are presented in Table 1. The benefit/cost ratio is calculated as 1.97 relative to conventional resource planning and the payback period is three years.

	<i>Conventional</i>	<i>BESS</i>	<i>Net Benefit (Cost)</i>
Load Following	\$3,870,000	\$0	\$3,870,000
Reserve Generation Capacity	400,000	154,000	246,000
Voltage Regulation	26,000	8,000	18,000
Customer Claims	31,000	0	31,000
BESS Operations	0	94,000	(94,000)
BESS Capital	0	2,023,000	(2,023,000)
	\$4,327,000	\$2,279,000	\$2,048,000

Table 1. Results of Metlakatla BESS economic analysis.

BROCKWAY STANDARD LITHOGRAPHY PLANT

The Brockway Standard lithography plant at Homerville, GA operates four production lines, two of them seven days a week. The plant prints labels directly onto sheet metal that is formed into cans for food, chemical, and specialty products (e.g., Folgers coffee, Eagle Snacks, Guy Foods, and Thompson Water Sealer) at Brockway can plants. Output averages 73½ sheets per minute when production lines are operating (roughly 40% or 10 hours of every 24-hour day). Brockway is a full-service shop, capable of handling artwork (label design and plate preparation at subsidiaries) and X-ray plates and screens processed on-site at Homerville.

There are approximately 16 motors per production line. In addition, there are motors driving the solvent disposal, incinerators, and other operations. Most equipment at the lithography plant dates back to the 1950s. Slash Pine, the local energy cooperative, is Brockway's electricity provider. Slash Pine is one of the 39 electric membership corporations that formed Oglethorpe Power Corp in 1974. In 1994-1995, with advice from Oglethorpe Power Corp., Brockway invested almost \$600,000 to upgrade many motors near the end of their useful life and install adjustable speed drives (ASDs) to control all the motors throughout the plant.

The ASDs at Brockway are far more sensitive to power glitches than the equipment they control. Slash Pine provided phase protection on-line, but Brockway was unable to control the ASDs during frequent lightning storms. These many power glitches caused their production lines to stop, which translated into substantial economic losses for the company whenever a power glitch occurred. Oglethorpe Power Corp., Georgia Power, and EPRI offered a solution – participate in an on-site demonstration of a power quality device known as the PQ2000.



Figure 1. The PQ2000 Brockway Installation

The PQ2000 was originally developed by Omnion Power Engineering under a 1994 cooperative agreement (DE-FC04-94AL99852) with the DOE, Sandia, AC Battery Corporation, and Pacific Gas & Electric. As shown in Figure 1, the system consists of a main system container that houses the batteries, a power controls cabinet that contains an electronic selector device (ESD), and an isolation transformer.

The Brockway PQ2000 battery system consists of 192 flooded lead-acid SLI batteries that are split into four modules (each contains 48 batteries) for a maximum discharge power of 1 MW. The transportable main system container can potentially contain up to eight battery modules, for a maximum discharge of 2 MW. Two battery modules sit on either side of the computer monitoring system that is located in the center section of the main systems container. The remote data acquisition system records data during voltage sags and also monitors system diagnostics.

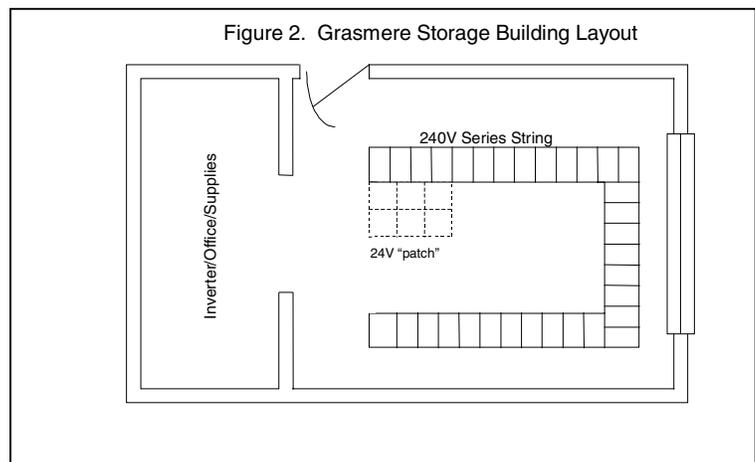
The PQ2000 takes approximately 1/240th of a second (<4 milliseconds or ¼ of a 60-Hz cycle) to respond and supply up to 1 MW for a maximum of 10 seconds during voltage sag events. Typical voltage sags are less than 10 seconds. In fact, most are shorter than 0.2 second (<10 cycles) in duration. If the controls detect a voltage sag, spike, or

interruption in any of the three phases, the electronic selector device in the power control cabinets isolates the lithography plant from the grid. The PQ2000 then provides the plant with high quality power for a maximum of 10 seconds, until the incident ends. The PQ device continues to monitor the incoming power during the incident and waits 0.2 second after power is within specified norms before transferring the plant load back to the grid. The power controls ensure that the PQ2000 and grid power are synchronous for smooth transition between the PQ device and the grid.

GRASMERE SYSTEM

The Grasmere Renewable Generation and Storage (RGS) installation supplies power for an Air Force training unit that provides electronic emission simulations for overflying military aircraft. It is staffed by a crew from nearby Mountain Home Air Force Base. The station is situated in mountainous terrain at the 5800 foot level and contains an office/communications building, a barracks, several storage/equipment buildings, high power radar and other emitters, water storage tanks, and a battery storage building. The power needs include housekeeping loads, water tank freeze prevention, and radar and other electronic equipment. The peaks involving the latter equipment are many times the basic housekeeping loads.

The lead-acid battery storage system consists of 120 Hoppecke Model 24 OpzS 3000 cells connected in a single series string of 240 volts nominal. The cells are rated at 3048 ampere-hours (20°C, 10 hour rate), resulting in a storage system rating of 732 kWh (3048 A-H x 240V). The positive electrode is tubular plate construction, each vertical tube having its own internal current collector. Negatives are standard flat plate design. Grids are lead, alloyed with 2% Antimony. According to the manufacturer, the cells are suitable for both deep discharge applications and float duty. The cells are vented and require periodic water maintenance.



As shown in Figure 2, the storage system is housed in a concrete and cinderblock building constructed specifically for that purpose. The roof is vented to allow hydrogen escape and appropriate sensors and safety equipment are installed. The battery's 120 cells are arrayed in a "U" shape in the building's main bay and ample space is available for cleaning and maintenance. A separate smaller bay houses the inverter, controls, a desk, and storage items.

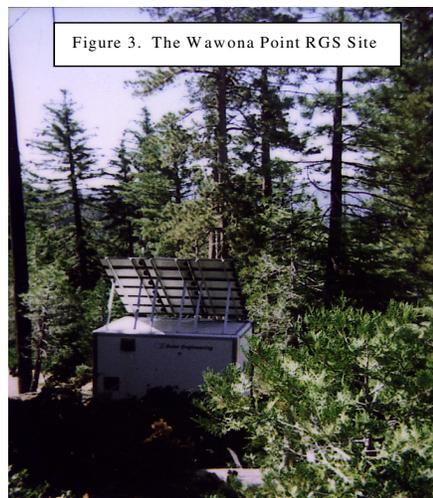
The battery was installed in January 1995. It was expected that relatively deep discharges would occur on nearly a daily basis. At this usage, some 360 deep cycles would occur each year and 5+ years would elapse before rated life of 2000 cycles was reached. However, there have been recent indications that there were two battery cycles/day, thus potentially surpassing the 2000 cycle expected life in a shorter time period. These clues suggested that the batteries were at, or approaching, end of life.

Wawona Point, Yosemite National Park

The PG&E Research and Development Department initiated a feasibility study in 1993 for supplying power to customers in off-grid locations. Applied Power Corporation (APC, formerly Solar Engineering Services) of Lacey, Washington, was awarded the contract to design and build a PV/propane hybrid power system capable of supplying 5 kWh/day through a standard 240 Vac service hookup. The system was packaged in a shipping container that could be installed without a permanent foundation so it could be easily installed and removed. As shown in Figure 3, the Off-Grid Power System (OGPS) is located about 100 feet west of a helipad on a mountain peak known as Wawona Point about 10 miles east of the south entrance of Yosemite National Park. The peak overlooks Wawona Valley from the south. A two-way radio repeater used for emergency and operating communications within the park is located about 50 feet east of the helipad. A television translator is located several hundred feet to the northwest of the helipad, which provides TV signal to several buildings and residences in the valley below. 240Vac utility power is supplied through a cable running up the slope from a utility transformer and revenue meter located about 0.5 miles

west of the helipad. While there is a road to the site, it is snow-bound during the winter, accessible by foot or by snowcat.

The radio-repeater and television translator each require about 5 kWh/day, together, twice the design capacity of the OGPS. The radio repeater is a critical element of the Park Service emergency communications system. It includes its own battery bank, ac power is rectified to float the battery and power the radio. In the past, when there were utility line failures, Park Service personnel would install a small generator at the radio and hope that the PG&E line would be repaired before the generator ran out of gas and the backup batteries were depleted. It was determined that the OGPS would be used to power the radio transmitter only, leaving the TV translator utility connected. It was also determined to connect the utility to the Trace inverter to allow sellback of excess solar generation and to provide a secondary back up (to the PV and propane generator) since there was some uncertainty about both the load and the solar resource (especially the effect of tree shadowing).



LESSONS LEARNED

METLAKATLA The Metlakatla BESS data archive was stored in a compressed, proprietary format. It was not sequenced by time in a flat-file format since it was measured and stored on an exception basis. This created enormous difficulties in handling the data archive since it was necessary to develop and employ tools necessary for converting the data to a more usable format.

Historical archiving was not an important design objective of the data system. Instead, the design was made to provide data to operators in a real-time format by integrating the system into its larger utility SCADA system. Furthermore, since the utility SCADA system was being deployed at the same time as the BESS control system, the same process control software package was used for both. The decision to archive data in this way significantly reduced the data storage requirements. However, the cost of storage media has dramatically dropped since the initial Metlakatla installation, and the storage densities have improved. Consequently, future data systems can be designed to facilitate data archiving and analysis.

The distinct requirements of operations versus data archiving suggest a dual design with both SCADA for real-time control and standardized database format for historical archiving.

BROCKWAY STANDARD The effort to decipher the data acquisition system was particularly hampered by the lack of support from the battery manufacturer and access to the original programmers of the data acquisition system. Claims of proprietary information and confidentiality were the response to most questions, greatly limiting the ability to crack the code and convert the data to a more understandable, user-friendly format.

The BESS manufacturer was unwilling to share any information regarding charging profiles, claiming proprietary algorithms. The step-by-step equations are not what are needed, rather guidelines regarding the current level used during taper charges, etc. would have been sufficient to assist with the estimates. Indications regarding pulse charging would have also strengthened the effort. As a result, the charging data in our Access database is the least credible.

When the data management project began, the team experienced delays in obtaining information on PQ2000 operation and descriptions of the data acquisition system. Information was provided piecemeal and analysis was begun before the complete data set was delivered. Variable definitions were not provided until the project was almost completed because an Appendix with the descriptions was missing from a key document. The definitions still left questions unanswered, causing problems with interpretation. As a result, analysis was performed multiple times, resulting in lost labor hours and frustration.

GRASMERE The ability to collect, average over a defined period, and archive data implies an information processing capability. The further manipulation of data to develop measures that can serve as performance

evaluation checks represents only an extension of existing processing capability. For battery storage data management, several processing enhancements are recommended as a result of the Grasmere analysis. For each, acceptable ranges of performance values should be established, the violation of which would be highlighted as “alerts” at the next data-to-operator transmission cycle. Possible alerts include:

- Low or high cell voltage
- Low state-of-charge for extended period
- Low overcharge levels for extended period
- High temperature for extended period
- Excessive charge/discharge currents
- Data system non-operation

The rationale for the listed alerts is relatively obvious. The first 5 items represent battery abuse conditions whose persistence would contribute to shortening of battery life. In this sense, the data collection and processing system plays the vital role of storage system health monitor and diagnostic tool. The 6th alert simply indicates that the storage system’s health monitor is not functioning properly.

A caution is necessary when adopting data system extended processing: *information regarding the alerts should be placed in a separate data field.* In the Grasmere case, the numerical codes indicating data collection failures were recorded in the data field to which they applied. Since information about this practice was not supplied with the data base, the failure codes were initially computed as data values which resulted in errant conclusions regarding battery performance. Substantial repeat analysis was required after the use and placement of error codes was discovered.

While the data presented certain problems, as indicated above and in prior sections, the execution of certain preliminary “checks” could have exposed most problem areas. Other up-front precautions could also have avoided analytical dead ends and helped analysts to pursue the most fruitful approaches. These precautions include:

- Exploration for out-of-limits data
- Establishment of optimum handling of data gaps
- Identification of recording system failure modes

In almost all cases, a reasonable range of expected values for critical performance parameters (current from various sources, cell and string voltages, temperatures) can be established. The data base (assuming it has been entered into a computer) can then be searched for values outside the established range and judgments made regarding possible further examination of the identified values.

The presence of data gaps is virtually inevitable. As the data is processed, the analyst must instruct the processor (computer) on the methodology for treating gaps in the data stream. Since there are numerous choices, depending on the selected parameter, early effort to develop an optimum method for each parameter could avoid repeated calculation and graphic cycles later on.

Most data collection devices are programmed to provide some type of notice of temporary system failures. To avoid repeating the Grasmere experience where significant re-analysis was required after identification of error code placement, storage analysts would be well advised to learn early about the specific error codes of the equipment being analyzed.

Wawona Point, Yosemite National Park Analyzing recorded data usually provides many opportunities to wish that various portions of the data collection process were conducted differently. However, the practice of actually operating systems and collecting data tempers the expectation that everything will be fully documented or that every data record will be present and accurate.

Electrochemical battery systems are primarily characterized by voltage potentials, current flows, and temperatures. The instrumentation for these types of signals are all commodity items, but it is important to take care that the chosen hardware supports the accuracy needed for battery evaluation. This level of accuracy is usually higher than that required for simple control algorithms, so extra care should be taken when considering re-using signals from a commercial-grade control system for long-term evaluations.

Typical industrial-grade isolation amplifiers (used to protect the data recording device) have an overall accuracy specification of 0.1 to 1% of full scale, with additional error specs for temperature and power source variations. This means that it is possible for the amplifier to be 10% in error when the signal is 1/10 of full scale. In practice it would be overly conservative to assume this, but it emphasizes that the accuracy could be 2-3% of signal under relatively common operating conditions without violating the specification. Alternate accuracy specifications may be available, such as 1% of signal with a minimum error band of 0.25%. With a fixed error spec, current signals may be higher under discharge than charge, the apparent accuracy of the charge measurement may be different than the accuracy of the discharge. Which accuracy is better would depend on the cycling regime that the battery operates under: fast charge and slow discharge, or slow charge and fast discharge.

Thus, the both the actual accuracy specification and the way it is specified can affect the outcome. In general, current transducers should be specified with a percent-of-signal accuracy rather than percent-of-full-scale. Voltage and temperature do not typically experience such wide variations in lead-acid battery systems, so percent-of-full-scale is usually adequate. In addition, despite much higher claimed accuracy, practical issues including transducer error, contact resistance, and temperature effects limit current measurement accuracy to 1% at best.

Strictly speaking, sampling is short for “sample-and-hold”, a process by which an instantaneous signal value is retained. In more loose terms (as used here), sampling includes any necessary conversion to digital format, since analog data recording is practically never used anymore.

The most important parameter in sampling is the sample rate. The Nyquist sampling theorem states that the sampling frequency must be at least twice the highest frequency of interest present in the signal to avoid aliasing. Another way of looking at this statement is that the signal may not change its upward or downward trend more than once between two successive samples and still interpret the result clearly. However, this theoretical limit is not practical, since (as it happens) the theory assumes you have data for all time (an infinite amount of data). Practical amounts of data require that the sampling frequency be at least 3 or 4 times the highest frequency of interest.

High frequency can be a problem for data sampling devices designed to record data for extended periods of time, since there are practical and economic considerations driving these devices to sample relatively slowly. Channel count and amount of data compression processing at the point of sampling are two such considerations. The use of inherently noise-tolerant integrating analog-to-digital conversion may be another. Campbell dataloggers, for instance, can sample and process 12 channels two to ten times per second depending on the extent of the processing. The OGPS system was conservatively configured to sample once per second.

Thus, in a system similar to the OGPS, if there is switching occurring more often than once every few seconds the signal should be analog-filtered before being wired to the datalogger. (Some data sampling equipment may include terminals for wiring in resistor/capacitor filter networks at the point of connection.)

CONCLUSIONS

As a first cut at the development of a user database for future design assistance, the Database Management project yielded information as to how to proceed with the collection and analysis of data from new sites. It also provided guidance on how to design data acquisition systems to preclude the loss of data caused by poor DAS design and implementation. As more information is collected and integrated into the database system, the refinement of the information should help future system designers avoid the shortfalls discovered in these early Battery Energy Storage Systems.