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Lessons Learned from the Puerto Rico Battery Energy Storage System

English and Spanish Versions Available

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Abstract

The Puerto Rico Electric Power Authority (PREPA) installed a distributed battery energy storage system in 1994 at a substation near San Juan, Puerto Rico. It was patterned after two other large energy storage systems operated by electric utilities in California and Germany. The U.S. Department of Energy (DOE) Energy Storage Systems Program at Sandia National Laboratories has followed the progress of all stages of the project since its inception. It directly supported the critical battery room cooling system design by conducting laboratory thermal testing of a scale model of the battery under simulated operating conditions. The Puerto Rico facility is at present the largest operating battery storage system in the world and is successfully providing frequency control, voltage regulation, and spinning reserve to the Caribbean island. The system further proved its usefulness to the PREPA network in the fall of 1998 in the aftermath of Hurricane Georges. The owner-operator, PREPA, and the architect/engineer, vendors, and contractors learned many valuable lessons during all phases of project development and operation. In documenting these lessons, this report will help PREPA and other utilities in planning to build large energy storage systems.

Acknowledgments

Sandia National Laboratories would like to thank Dr. Imre Gyuk of the U.S. Department of Energy, Office of Power Technologies within the Office of Energy Efficiency and Renewable Energy, for support and funding of this work. We would like to acknowledge the Puerto Rico Electric Power Authority (PREPA), the owner of the battery energy storage facility. The utility provided access to the facility, archived files, and key staff (including retired PREPA employees) involved with the project from its inception. In particular, thanks are due to Efrén Román, Rafael Ruiz, Carlos Reyes, Angel Colón, Julio Quiñones, Luz Alemán, and Jesús Sánchez. We are also grateful to the key firms involved in the project, including Raytheon Engineers and Constructors, C&D Charter Systems, General Electric, and Applied Control Systems. They shared considerable information with us.

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Acronyms

AC	alternating current
ACS	Applied Control Systems
BESS	battery energy storage system
BEWAG	Berliner Kraft und Licht (German utility)
DC	direct current
FCS	facility control system
GTO	gate turn-off, type of thyristor
Hz	hertz
kV	kilovolt
MW	megawatt
O&M	operations and maintenance
PCS	power conversion system
PREPA	Puerto Rico Electric Power Authority
RFP	request for proposal
T&D	transmission and distribution
UE&C	United Engineers & Constructors
Vpc	volts per cell
VRLA	valve-regulated lead-acid

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1. Introduction

A 20-megawatt, 14-megawatt-hour battery energy storage system was installed in June 1994 at the Sabana Llana substation near San Juan, Puerto Rico, primarily to mitigate under-frequency load shedding. It was patterned after two other large energy storage systems in California and Germany and is at present the largest operating battery storage system in the world. (see Figure 1-1) The owner-operator, Puerto Rico Electric Power Authority (PREPA), and the architect/engineer and supplier firms learned many valuable lessons, from planning through the first four years of operations. This report documents these lessons and will help PREPA and other utilities use this experience in planning to build additional large energy storage systems for frequency control, voltage regulation, and spinning reserve.

Since it first began operations in 1994, the battery energy storage system (BESS) has responded to dozens of load shedding events and continuous demand for frequency regulation. Almost every key component experienced some problem during initial start-up and operations. PREPA and their vendors and contractors have solved many of these problems. Still, other challenges remain. Despite these problems, however, the BESS performed admirably in the aftermath of the worst hurricane to hit the island this century. The plant was able to maintain voltage support on the only transmission line from San Juan to the northeastern region that was still operating after the hurricane.

PREPA plans to construct a second BESS at the Sabana Llana substation (see Figure 1-2). This second facility was originally scheduled to come on line in 1998; however, construction of a large combined-cycle plant on the island consumed much of the capital improvement budget. PREPA currently anticipates beginning the planning and design phases of its second BESS in fiscal year 2000 (July 1999–June 2000), with construction starting in FY2002. PREPA served as the system integrator for the first BESS, but it is unlikely that the utility will perform that role for this second facility. PREPA is currently planning for a turnkey facility, with its performance guarantees and reduced stress on the owner during design, procurement, construction, and initial start-up. The utility, however, will undoubtedly be an active participant in this project.

PREPA's experience identified many pitfalls as well as optimum processes for planning, design, procurement, construction, operation, and maintenance of a large, integrated energy storage facility. This Lessons Learned document will be useful to the other utilities considering construction of similar facilities

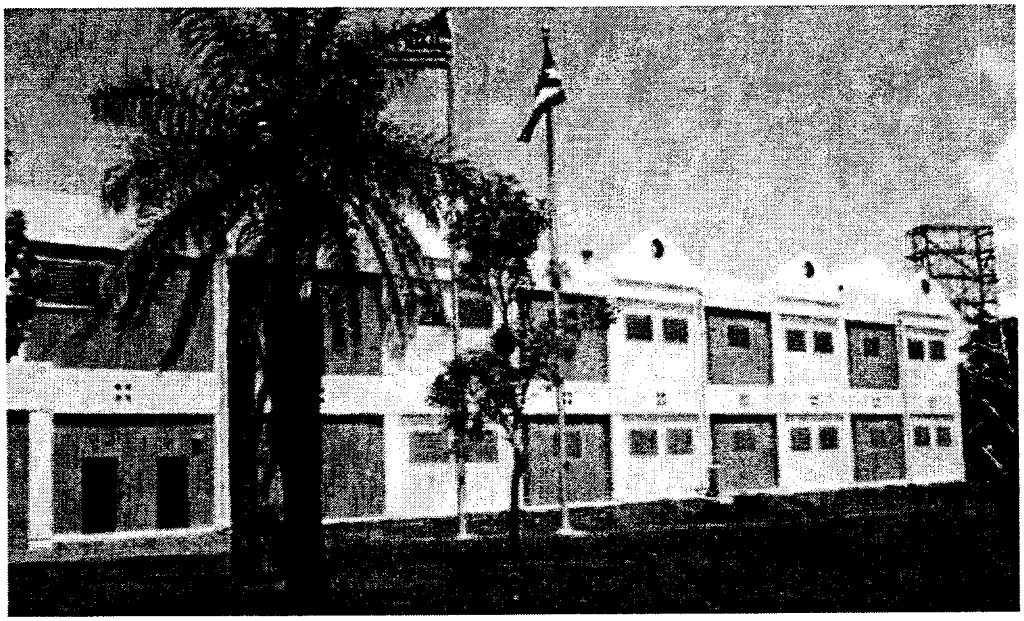

Figure 1-1. Battery System Building in Puerto Rico.

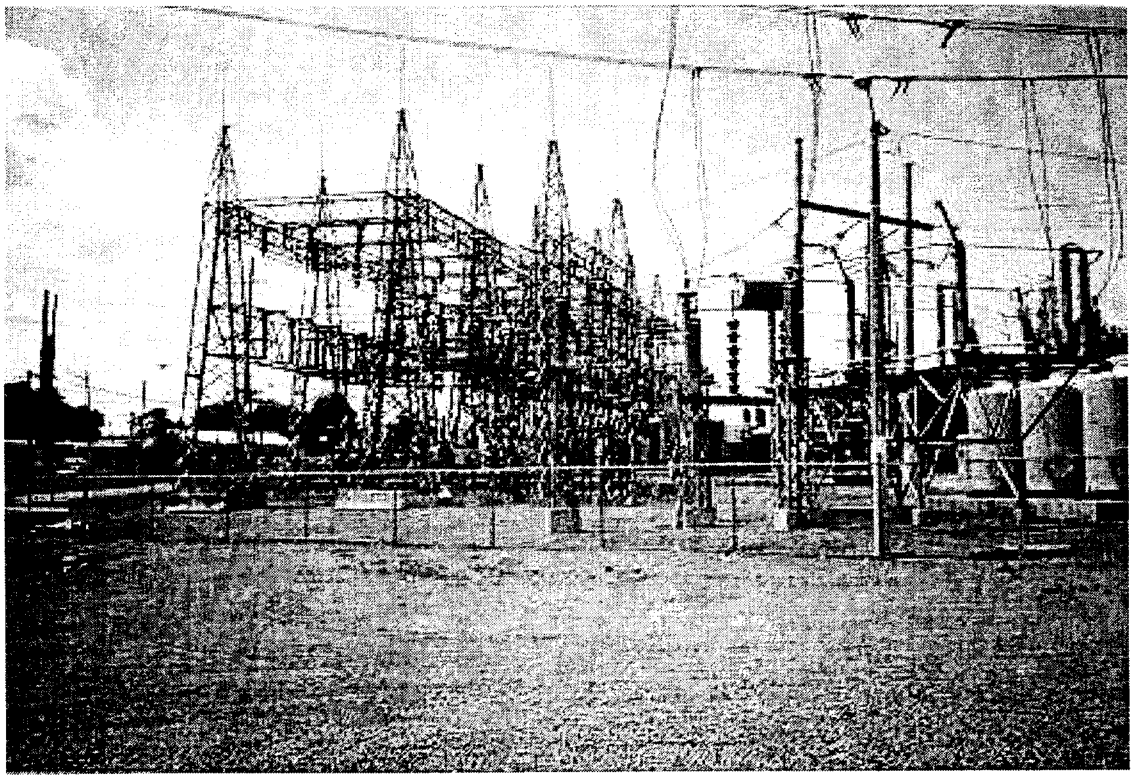

Figure 1-2. Sabana Llana Substation.

2. System Description

2.1 Historic Perspective

PREPA is a public corporation and government agency that was founded in 1941. As of July 1999, it provided electric energy services to 1.3 million clients, with a peak load of 3,057 MW and annual sales of 17 million MWh. PREPA produces, transmits and distributes, practically all the electric power used in Puerto Rico. The utility is directed by a Governing Board of nine members. The Board appoints an Executive Director, who runs the day-to-day operations of the utility.

Five power plants with a capacity of 4,397 MW, produce most of the electricity on the island from distillate and residual fuel oil. The transmission system consists of 2,272 miles of 230 and 115 kV transmission lines, and 38 kV sub-transmission lines. Sabana Llana is one of the 178 transmission centers in the system (see Figure 2-1).

Throughout the 1970s and 1980s, PREPA experienced operating problems due to its island status and the relatively large size of its oil-fired power plants. Sudden outages of 400-MW units caused instantaneous overloads of 15–20% in the network. Frequency instabilities resulted whenever the steam generators did not respond as rapidly as needed. To prevent damage to steam plants at low frequency, automatic load shedding was implemented, affecting all classes of customers and threatening Puerto Rico's industry and commerce.

In the early 1980s, engineers at PREPA began investigating alternatives to prevent load shedding and provide frequency control. They developed a plan of action that was passed by the Governing Board as Resolution 2265 on December 12, 1989. Specifically, the resolution called for:

- Increasing the availability of existing units
- Improving the load response of existing turbo-generator units
- Requiring all new combustion turbines (utility and non-utility) to provide fast spinning reserve
- Installing 100 MW of immediate-response energy storage throughout the network

In 1990, PREPA's Governing Board gave authorization to design the first 20 MW of battery energy storage. Design, engineering, and procurement proceeded through 1992, with construction initiated in August 1992. The building was completed in October 1993, and the plant was inaugurated in July 1994.

2.2 System Configuration

The BESS is located at the Sabana Llana substation and consists of six main subsystems (see Figure 2-2):

- Batteries and auxiliaries
- Power conversion system
- DC switchgear
- AC switchgear
- Main power transformer
- Facility control system

The BESS plant is housed in a two-story reinforced concrete structure and includes a transformer yard. Massive structural columns and beams were used to support the weight of the batteries and to provide stability in a seismically active zone (uniform building code, UBC Zone 3).

Batteries and Auxiliaries. The facility has a nominal DC power rating of 21 MW, for a total output of 14 MWh. The nominal discharge duration to 1.67 volts per cell (80% depth-of-discharge) is 40 minutes. The BESS consists of two 10-MW battery modules, each located on a separate floor of the two-story structure. Each module has 3,000 flooded lead-acid cells arranged in three parallel strings of 1,000 cells. The maximum current per string is 2,000 amps at 1.67 volts per cell (Vpc). Each string produces a maximum of 2,380 volts at top of charge. The cells are installed in double-tiered, back-to-back racks. C&D Charter Power Systems is the manufacturer and vendor of the 6,000 cells (see Figure 2-3). The specialty cells were assembled according to the following specifications:

- Capacity per cell:
  - 1,536 amp-hours (40-minute rate to 1.67 Vpc)
  - 2,265 amp-hours (5-hour rate to 1.75 Vpc)

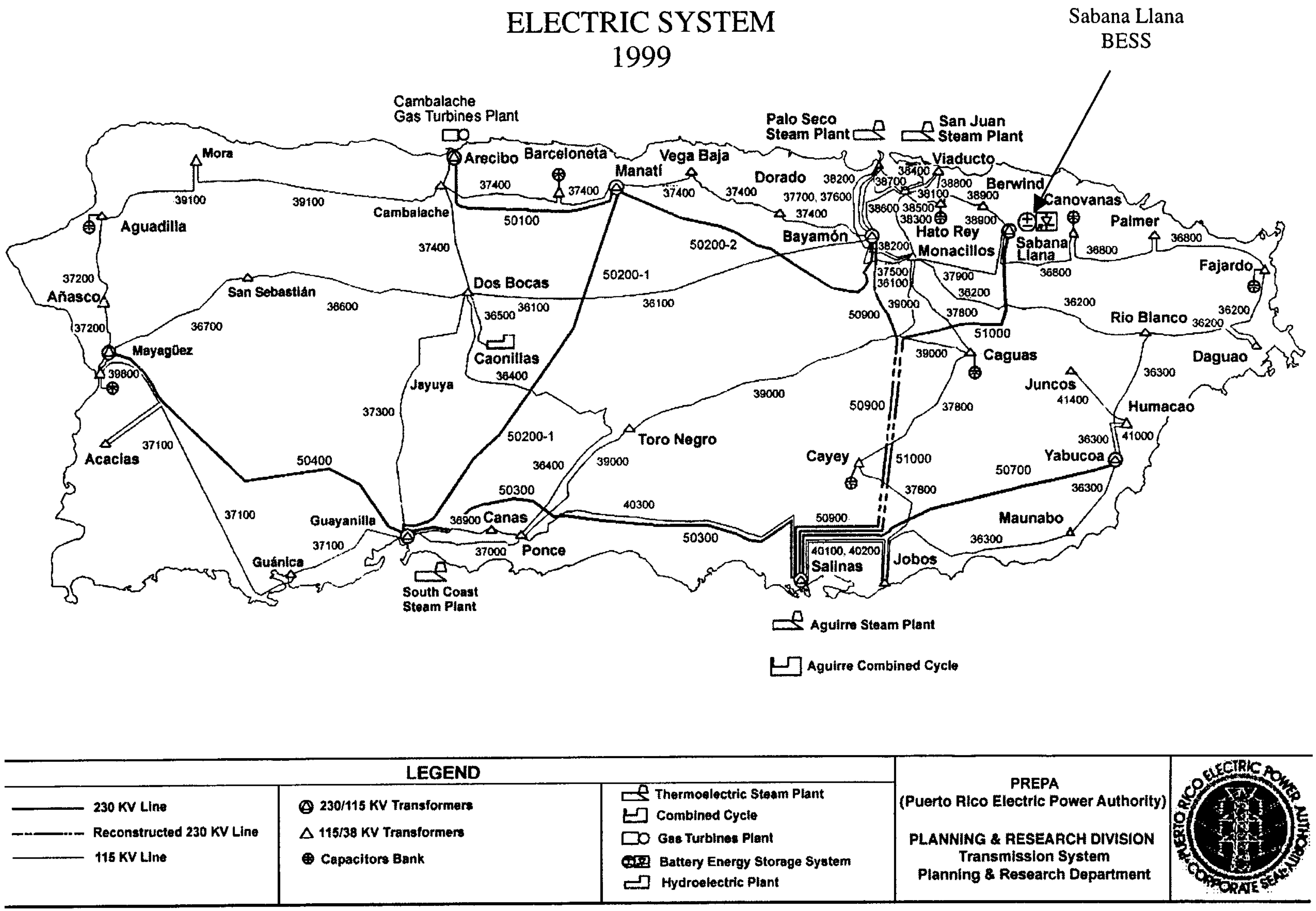

Figure 2-1. PREPA Electric Grid.

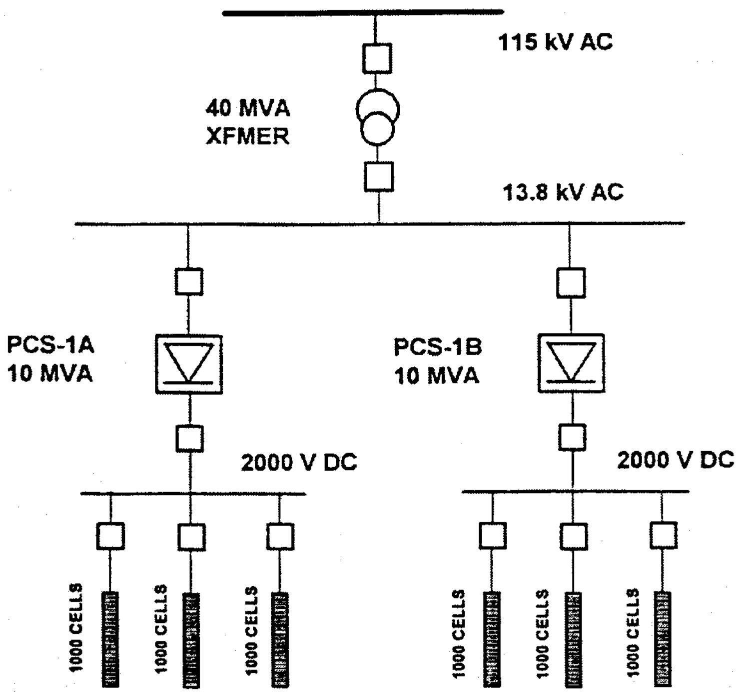

Figure 2-2. BESS Schematic Diagram.

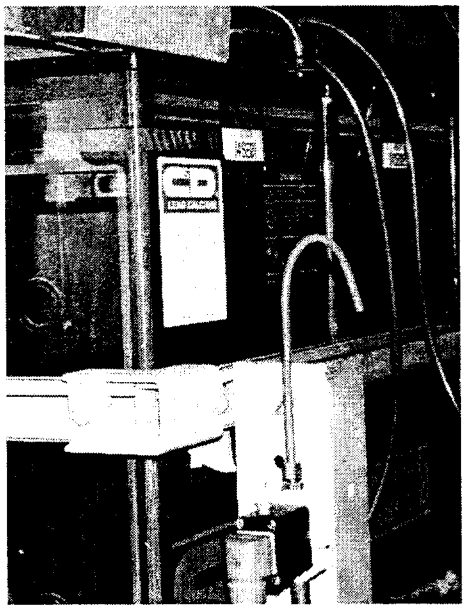

Figure 2-3. C&D Lead-Acid Cells.

- 24 positive and 25 negative flat plates
- Separated by isolating mats
- Lead-calcium alloy grid
- Wrapped positive plate

The cell dimensions and weight are:

- 22" high × 13" wide × 14" deep
- Weight 460 lb (filled)

A watering system and air agitation system were also supplied by the battery vendor. Every six hours, the air bubbling system is activated for 15 minutes to avoid stratification of the acid in the cells. It is primarily needed when the battery is operated in frequency regulation mode.

Power Conversion and Balance of Plant. Two power conversion systems (PCS), each sized at 10 MVA, were supplied by General Electric. Each PCS consists of:

- Three 6-pulse gate turn-off (GTO) bridges
- GTO thyristors rated at 4,500 volts and 2,500 amps (see Figure 2-4)
- Three transformers (one 2-winding, two 3-winding)
- Harmonic filter capacitor bank rated at 2.7 MVAR
- Control subsystem

The DC switchgear was custom-built by Power and Control Systems (PACS), and consisted of a variety of components from other manufacturers. High-speed DC breakers from Ansaldo provide protection against faults occurring on the battery strings. Fuses

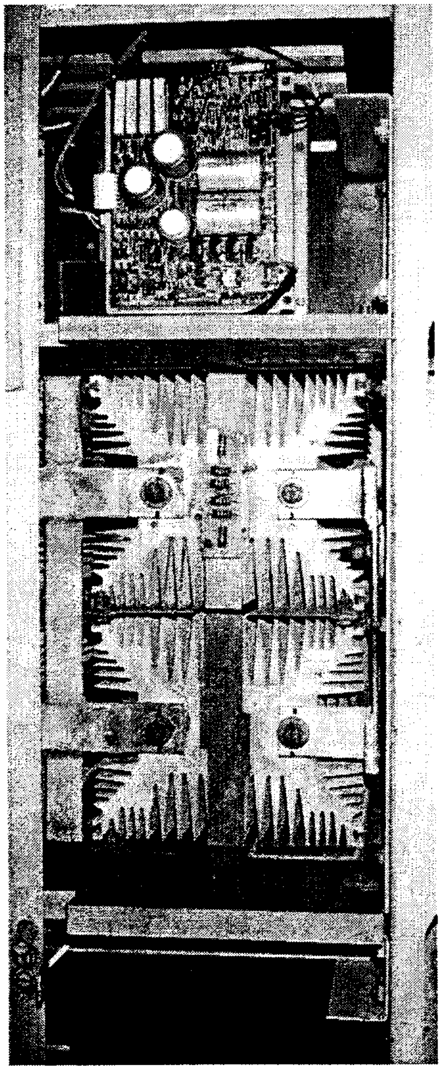

Figure 2-4. GTO Inside PCS.

from Ferraz provide back-up protection. Isolation switches from Pringle separate the 1,000 cells in each string into groups of 170 cells, which together with the ground detection system from ABB, enhance personnel safety during maintenance. The AC switchgear was supplied by ABB and Pauwells supplied the main power transformer.

The facility control system (FCS) was supplied by Leeds and Northrup, and programmed by Applied Control Systems. The FCS consists of four components: fiber optic data highway, distributed processing units, application processor and workstations, and cell voltage and temperature monitoring (OPTO-22). All battery subsystems and auxiliaries are controlled by the FCS, which uses a control strategy based on amp-hour and state-of-charge calculations.

2.3 System Functions

Energy storage systems support generation, transmission & distribution (T&D), and customer applications. The BESS in Puerto Rico supports generation with rapid reserve and frequency control, T&D with voltage regulation, and customers with more reliable service.

- Spinning reserve is defined as the unused generation capacity that is synchronized to the network and can respond within ten minutes to prevent interruption of service to customers (load shedding) in the event of a failure of an operating power plant.
- Rapid reserve is a portion of spinning reserve that is available almost instantaneously to prevent automatic load shedding.
- Frequency control is the regulation of frequency of the electricity that utilities produce within a narrow band around 60 Hz.
- Voltage regulation is the ability of a power source to maintain constant output voltage with changes in load.

Rapid reserve is power available to the system within three-to-five seconds after an outage of a central station unit occurs on the network. It requires a quicker response than spinning reserve, which is available to the system within ten minutes after a generation outage occurs. Rapid reserve is a requirement for all facilities built by PREPA since Resolution 2265 was issued in 1989. Select generation units (e.g., Cambalache gas turbine power plant) and the BESS can provide rapid reserve power in case of a large unit trip, minimizing load shedding.

Operating in rapid reserve mode, the BESS is available at full capacity for up to 15 minutes, allowing start-up, synchronization, and load pick-up by an emergency combustion turbine. The BESS can ramp down to zero in another 15 minutes. The BESS was designed to perform this duty starting from a minimum 70% state-of-charge an average of 55 times each year. After each rapid discharge event, the BESS receives a refresh charge to 100% state-of-charge after midnight or during another convenient off-peak period. There are three triggers for rapid discharge:

- Frequency decays at a rate of 0.25 hertz/second (Hz/s) or more when system frequency is between 59.4 and 59.6 Hz

- Frequency drops to between 59.2 and 59.0 Hz for a period of 30 seconds or more
- Frequency falls below 59.0 Hz

BESS response to a significant frequency drop at 1 PM on May 2, 1997 is illustrated in Figure 2-5. Within five seconds, frequency dropped below 59.0 Hz, triggering the BESS 1.5 seconds later. The BESS responded with full capacity (20 MW) in just over one second. The immediate BESS response helped PREPA quickly recover frequency within one minute, and kept system-wide load shedding to a minimum.

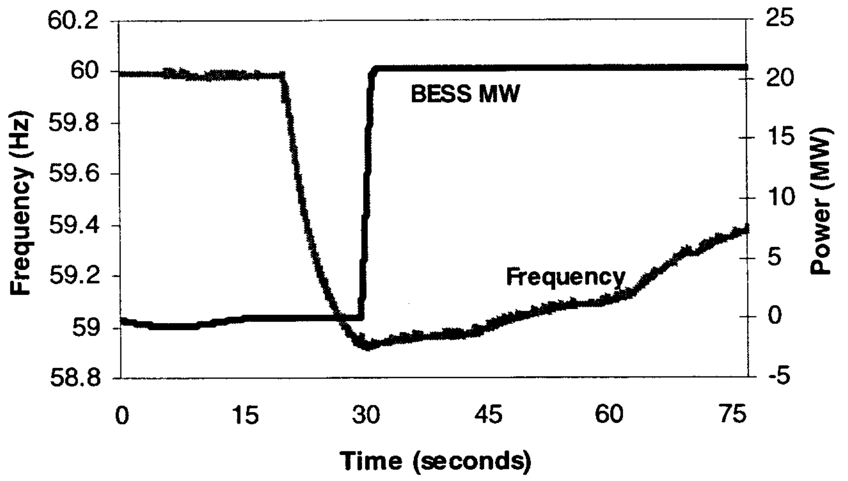

Figure 2-5. Immediate BESS Response on May 2, 1997.

A secondary function of the BESS is frequency control to eliminate small deviations (+/– 0.2 Hz) of system frequency from its nominal 60 Hz value. The BESS continuously charges or discharges up to 10 MW in proportion to the frequency error signal. Limiting the maximum discharge to 10 MW helps conserve stored energy for rapid reserve operations. Frequency regulation operation is conducted as long as the battery state-of-charge exceeds 70%. Frequency regulation produces continuous cycling of the cells.

The BESS also provides voltage regulation, operating similarly to a synchronous generator or condenser capable of supplying or absorbing reactive power. Most of the time, the reactive power is supplied up to the capacity of the power conversion system (20 MVA), and voltage at the Sabana Llana substation is maintained at 115 kV.

The BESS experienced its first rapid discharge on November 23, 1994. A 410-MW unit of PREPA's South Coast Steam Plant was lost, resulting in a 21% system overload. Load shedding was necessary, but the magnitude of the event was reduced by 80 MW due to the availability of the BESS.

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3. Lessons Learned

The lessons learned are presented by project phase to indicate the type of challenges that can arise during each phase of a project. In particular, this organization of the report identifies specific successes, difficulties, and resolutions in a way that potential BESS developers and owners might find useful. This project was initiated in 1989, with internal planning documents prepared by the PREPA Planning Division with assistance from its architect/engineer, United Engineers & Constructors (UE&C). The utility evaluated alternative technologies, including batteries, flywheels, and gas turbines to combat frequency control issues that caused load shedding. PREPA determined that a BESS would provide the quickest response to power fluctuations and achieve the fastest payback.

Six phases of this project over ten years are identified in the timeline in Figure 3-1. A variety of problems emerged in each of the project phases, which are discussed in the following sections, with lessons learned highlighted in bold.

3.1 Planning

PREPA's Planning and Research Division directed the planning phase. PREPA's architect/engineer UE&C was invited to evaluate the underlying analysis in the planning documents prepared by PREPA. In addition, as word spread about PREPA's plans, a number of energy storage system suppliers began to approach both PREPA and UE&C. The planning staff had found a dearth of information on the subject of utility energy storage and met some skepticism on its application from influential members of senior management. Fortunately, PREPA was able to draw upon the experience of two large BESS facilities already in operation: Southern California Edison's 10-MW/4-hour Chino facility operating since 1988 and Berliner Kraft und Licht's (BEWAG) 17-MW/30-minute battery plant operating since 1987. Specific lessons learned from PREPA's planning experience follow.

Establish a team to follow the project through completion. PREPA successfully organized a team consisting of staff from its Planning, Operations, Generation, Transmission & Distribution (T&D), Maintenance, Construction, Purchasing, and Finance Departments. The team was created early in the planning phase, and provided continuity in this first-of-a-kind project (see Figure 3-2). This team approach increased management confidence in the project through construction.

Identify up front who is responsible for the system within the organization throughout all project phases. The original plan was for the plant to be a dispatchable resource in the T&D section of the Operations Division. However, Operations management decided to place the facility in the Generation Division, which was not initially involved in

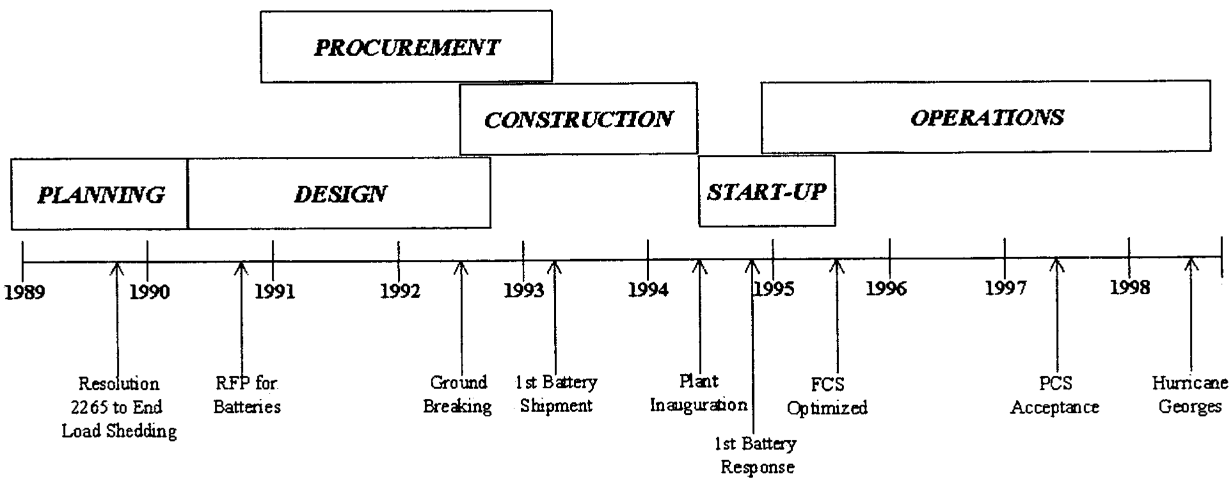

Figure 3-1. Project Timeline and Key Milestones.

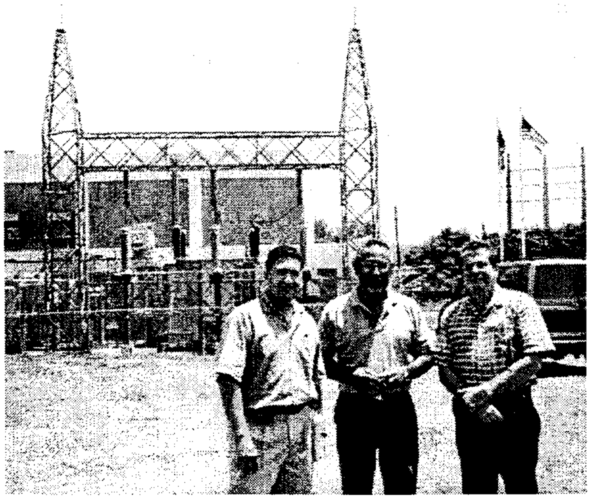

Figure 3-2. Key Construction, Operations, and Maintenance Team Members.

the BESS project. Further, direct responsibility was given to the group in charge of distributed generation assets, which comprised small hydro and gas turbine plants dispersed throughout the island. Although the BESS was seen to fit the distributed resource model, the unfamiliarity with its operational concept caused some difficulties during the transition from construction to operations.

Determine project responsibilities for all participants before going to procurement. Normally, an architect/engineer requests control of the procurement process for smoother scheduling and speedier project completion. UE&C's original proposal assumed that the contractor would select all vendors and purchase all equipment on behalf of PREPA. However, PREPA's Engineering Division determined that the utility legally could not allow the architect/engineer to buy its equipment. It was determined that PREPA must administer all bids, select the lowest evaluated bidder, and coordinate delivery and installation of all equipment. Delays caused by this process resulted in a UE&C contract extension and cost overrun of 50% above the original contract price. This occurred even though the firm had only a design role (preparing specifications and identifying potential bidders for bid documents) and an advisory role in evaluating vendors. A complex decision-making process held up progress, perhaps delaying construction completion by one year.

Coordinate meetings with licensing boards to facilitate the permitting process. PREPA was pleased with the handling of Environmental Quality Board permits. The BESS was the first-of-a-kind installation in Puerto Rico. PREPA personnel were concerned that the permitting process would be difficult so they requested a meeting of the board rather than simply submitting a package for their review. At the meeting, PREPA presented information on the environmental impacts of the lead-acid cells with lead calcium grids proposed by the battery vendor. These cells produce less hydrogen gas and require less watering than cells with lead antimony grids, which assuaged the Board's concerns and expedited the receipt of the permits. For this first-of-a-kind system, these face-to-face meetings significantly eased the permitting process.

Gather and evaluate as much performance data on other facilities as possible. PREPA's Planning staff admit that they probably were not sufficiently thorough in collecting data on the performance of the Chino and Berlin facilities. BEWAG and Southern California Edison staff were invited to debrief PREPA, and UE&C staff and facility visits were organized. Although the BEWAG battery plant was identified as the facility that mirrored PREPA's intended application, a formal consulting relationship was never established with BEWAG. The German utility and its engineering firm, EAB, did perform incidental consulting on the cell monitoring and control system. However, BEWAG and EAB could have assisted PREPA staff in answering many questions that kept resurfacing throughout the project regarding the performance of different cell types (e.g., lead antimony and lead calcium), cell watering systems, PCS, DC switchgear, and control systems.

3.2 Design/Engineering

PREPA staff had considerable communications with UE&C, who directed the Design/Engineering phase. The utility wanted to make certain that the BESS was not a first-of-a-kind demonstration like the Chino and BEWAG plants. They insisted that all subsystems consist of commercially available components, however, very few components were in fact purchased off the shelf. In addition, PREPA did not want a turnkey project in which they would have minimal involvement; the utility wanted to be the system integrator. These two conditions significantly impacted the design/engineering phase.

Select the architect/engineer with the most relevant experience. UE&C, preceded by Jackson Moreland and since sold to Raytheon, has been the PREPA bondholders' engineering consultant for over 30 years. UE&C performs all due diligence work and prepares annual reviews for all major plant projects in the capital improvement budget. Originally UE&C seemed a reasonable choice for the design/ engineering firm since it was the designer for the Chino BESS. The BEWAG facility, an electrical island in East Germany before reunification, more closely modeled the PREPA BESS. In hindsight, PREPA should have worked more closely with the engineers who were responsible for the design used by BEWAG.

Be an active participant in system design. PREPA was pleased with its coordinated development of specifications for major subsystems. Design of the voltage monitoring and facility control systems were greatly enhanced by PREPA participation. The architect/engineer prepared specifications for six major subsystems, and PREPA reviewed the specifications before entering the procurement phase.

Accept that project phases are intertwined in large competitive solicitations. Until the suppliers are selected, final subsystem and interface requirements are not completely known. This project involved seven sequential competitive solicitations. The design, procurement, and construction phases were intertwined for different subsystems. The design for the building could not be finalized until the batteries were selected. Likewise, the short-circuit capability of the AC switchgear depended on the choice of the PCS and transformers. These overlaps are not unique to this project; however, they required additional coordination by PREPA.

Verify available infrastructure before preparing an appropriate design. PREPA did not realize that the site selected had insufficient municipal water flow for fire protection. PREPA had to install a large water storage tank and pump house for the sprinkler system at an additional, unexpected cost of $250,000 (see Figure 3-3).

Identify and design for site-specific environmental and climatic conditions. Based on PREPA's Maintenance staff experience with standby stationary batteries at all substations, the ambient temperature where the batteries would be housed was likely to be in the upper 80s° F. These temperatures disqualified valve-regulated lead-acid (VRLA) in favor of flooded lead-acid batteries. There were extensive discussions on the type of flooded lead-acid cell to be used. Consideration was given to flat-plate and tubular cell designs, and to various lead alloys for the grid construction. Flat-plate flooded lead calcium cells were

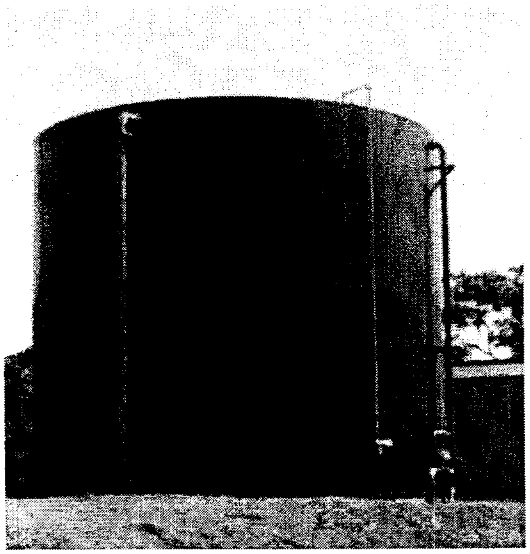

Figure 3-3. Fire Tank at the BESS.

selected. Initial concerns about the adequacy of lead calcium cells for cycling duty were overcome by assurances from the manufacturer about its special design considerations, including wrapping of the positive plates. Sandia National Laboratories modeled the thermal behavior of the cells to prove that fans would be sufficient to keep them in an acceptable temperature range.

However, the design of the air handling system for the PCS electronics room proved to be inadequate. After about a year and a half of operations, it became evident that many outages of the PCS were being caused by corrosion on gold-plated connectors on electronic circuit boards (see Figure 3-4). Metallurgical and environmental analysis by Corrotek Corp. demonstrated that the combination of high humidity and salt mist contamination present in the coastal environment caused the corrosion problem. The PCS cooling system, based on exhaust fan blowers and intake air filters, maintained adequate temperature and control of dust. However, it actually exacerbated the acidic and humid conditions, which led to frequent failure of the circuit boards. PREPA and GE shared the cost of installing the new refrigerated air cooling system in October 1996. PREPA then removed and cleaned all the gate driver cards and painted the cabinet doors for the PCS controlling the second-floor batteries (PCS 1B). The PCS controlling the first-floor batteries (PCS 1A) was left in its corroded state. Figures 3-5 and 3-6 show the cabinet doors with and without corrosion today. After January 1997, PCS performance improved dramatically and the second-floor PCS showed no signs of further corrosion.

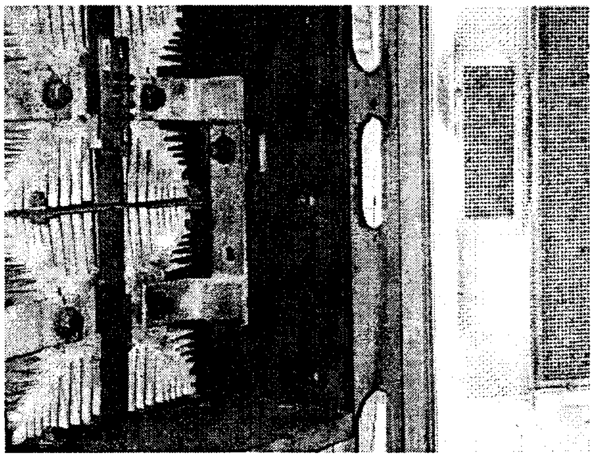

Figure 3-4. Corrosion on PCS Cabinet and Door.

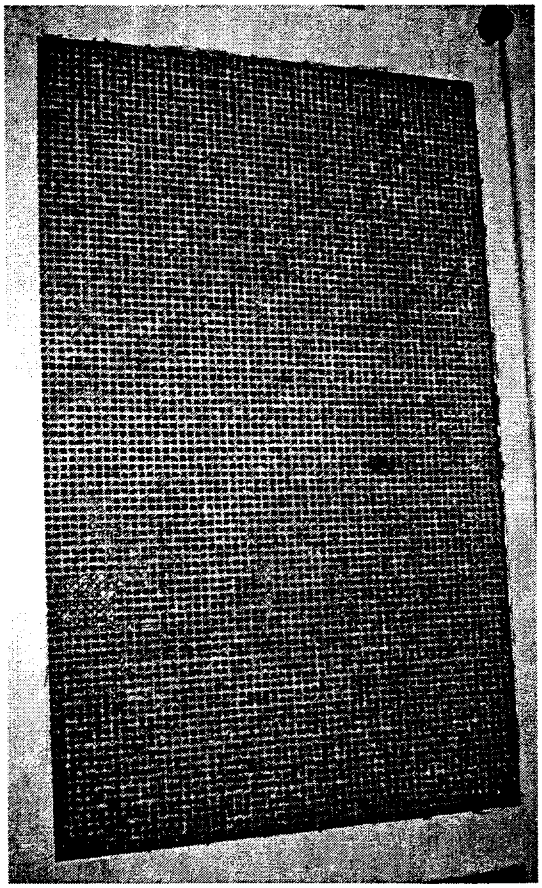

Figure 3-5. Corroded PCS Cabinet.

Design the building to facilitate regular maintenance and major overhauls. Some building design features make maintenance difficult. With the plant's location at a busy intersection of two highways, dust is a frequent problem, and air filters require frequent changing. PREPA wished it had installed sliding ladders, stairs or other equipment to facilitate

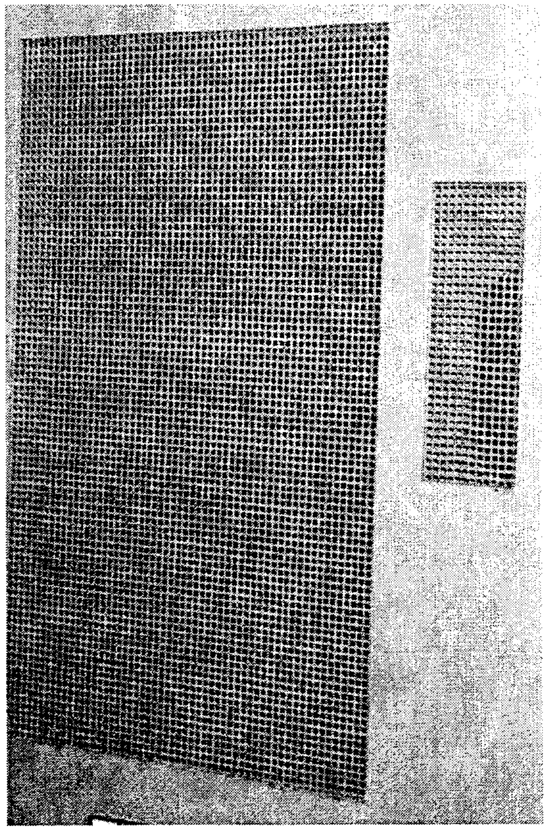

Figure 3-6. Clean PCS Cabinet.

replacement of the hundreds of air filters located on the 30-foot wall at the rear of the PCS room. PREPA never could replace the upper air filters because they were located above high-voltage electrical equipment and cables in a narrow space. Likewise, none of the fans could ever be replaced because the parts cannot fit through the standard double doors that are the only ingress/egress to the building. These design flaws were no longer important after the air conditioner was installed.

Large sliding gates or shutter doors on rollers should have been designed to permit moving a large number of batteries in and out of the building. Further, a cargo elevator, not just an equipment hatch, should have been installed in order to lift more than one cell at a time to the second floor (based on BEWAG's experience). By the end of 1998, PREPA purchased a one-ton hoist and was building a metal box with sides and runners to lift four cells at a time to the second floor. The design of the battery racks (see Figure 3-7) makes removal and replacement of some cells very time-consuming. Long horizontal bars must be removed to access cells on the lower rack and for cells located behind the vertical supports, an adjacent cell must first be removed before the desired cell is

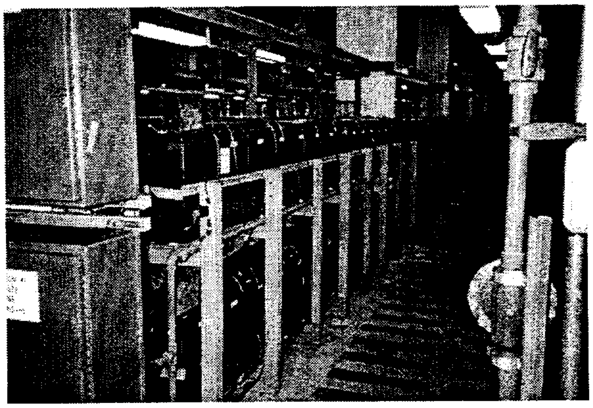

Figure 3-7. Batteries on Racks with Lower Horizontal Bar Removed.

slid over and removed. The original building design also did not include storage rooms for replacement parts, additional components, and computer-related materials.

Consider the performance and cost implications of subsystem design and configuration. The BESS must respond quickly when called into service. At PREPA, when a generating unit goes off line, the frequency can fall below acceptable limits in less than three seconds. As initially designed, the system frequency monitors were connected to the facility control system which triggered the BESS response. This system was too slow, resulting in a response time greater than the required 1.2 seconds. The cause of this problem was mainly due to the long scan rate of the control system, which had been specified as 125 milliseconds, but had increased to more than 300 milliseconds as the control loops became more complex. ACS worked intensively to optimize the control logic code and the scan rates were reduced substantially. However, in the end, the problem was corrected by hardwiring the under-frequency signal detectors directly to each PCS control (see Figure 3-8), bypassing the FCS in rapid discharge mode. From the instant the PCS receives a signal from the relay that frequency decay exceeds acceptable limits, each PCS responds, on average, within 300 milliseconds with its full 10 MW output. This design issue, identified during initial start-up, cost PREPA time and money in corrective actions.

Another expensive design trade-off derived from the 2000V input voltage requirement of the PCS. This voltage was higher than most commercial-grade systems and required a special design and fabrication of the metal enclosure containing circuit breakers, isolating switches, fuses, shunts, and ground detection system (see Figure 3-9). The custom-built switchgear

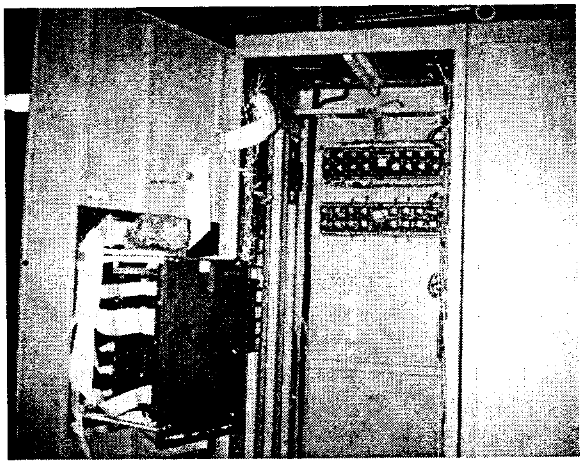

Figure 3-8. Master Controller for PCS.

Figure 3-9. DC Switchgear.

had to interrupt a very high DC short-circuit current, making it more costly than anticipated The DC switchgear Request for Proposal (RFP) was amended twice because none of the bidders could meet the original specification.

3.3 Procurement

PREPA coordinated the procurement processes. Having a public power authority control procurement extended a complicated process, with seven sequential solicitations, into a two-year effort. In addition, PREPA had not built a major facility for 15 years. The last was two 300-MW combined cycle turnkey plants whose development was spurred by the promises of a blossoming petrochemical industry. Nonetheless, PREPA staff undertook a number of initiatives that paved the way for construction.

Dedicate a purchaser in the organization to ensure good communications and project continuity. PREPA assigned one purchasing agent to the project. He successfully coordinated seven competitive bids, in sequence, including several addenda to the original RFPs. PREPA issued all RFPs and evaluated all bids, with assistance from the architect/engineer, for the batteries and auxiliaries, PCS, transformers, AC switchgear, DC switchgear, control systems, and building construction. Having one person in charge of all the procurements ensured this successful coordination.

Budget for cost variations. The original budget for the BESS was approximately $15 million, based on planning cost estimates prepared by the architect/engineer in 1989. After the bids of all contractors were received in 1991, the cost estimate rose to $16.8 million. Upon inauguration in 1994, the final cost of the BESS reached $20.3 million (see Table 3-1).

The final costs rose for a number of reasons. For example, the transformer costs almost doubled because it was decided to purchase a unit with a nonstandard impedance and double the required capacity in anticipation of installing a second 20-MW BESS at the same site.

Ensure that all potential bidders are invited. PREPA suggested that their process did not ensure that UE&C always identified the best potential bidders for all components.

Design specifications that avoid multiple interpretations. Five companies were invited to bid on the batteries, of which four responded. The battery capacity and price submitted in the bids varied significantly as a result of different interpretation of the specifications. The main reason for the confusion was the requirement to size the battery to allow for continuous frequency control operation, while conserving sufficient capacity for rapid discharge. A standard sizing procedure for such a requirement does not exist. Depending on the initial assumptions and the calculation methodology, different size batteries can be chosen. For this reason, the initial bid had to be cancelled. By consulting with battery specialists familiar with the intended applications during the writing of the specifications, BESS developers and owners can avoid important omissions and guidelines necessary for the appropriate design of the equipment.

Develop contingency plans for off-schedule equipment deliveries. Construction or manufacturing delays in one subsystem resulted in other hardware being delivered earlier than it was actually needed for installation. For example, delays in the

Table 3-1. PREPA BESS Costs by Components (Million $)

Contractor	Principal Components	Proposed Bid	Ultimate Cost
United Engineers & Constructors	Design/Engineering	0.95	1.49
C&D Charter Power	Batteries, Racks, Watering System	4.60	4.84
General Electric	PCS	5.40	5.40
Pauwels	Transformers & 115 kV Interface	0.36	0.70
ABB	AC Switchgear	0.19	0.19
PACS Industries	DC Switchgear	0.50	0.72
Leeds & Northrup/Applied Control Systems	Facility Control System & Monitoring	0.80	1.33
Aireko	Construction & Balance of Plant	4.00	4.85
PREPA	Project Mgmt, Training, Testing	----	0.80
TOTAL		16.80	20.32

selection process and construction of the building resulted in the batteries being delivered long before they were actually needed. Batteries standing for a long time will self-discharge. Based on PREPA experience with other battery back-up systems, they purchased six chargers and began recharging the cells in small strings once every three months (see Figure 3-10). Each charger can fully recharge 56 cells at a time within two hours.

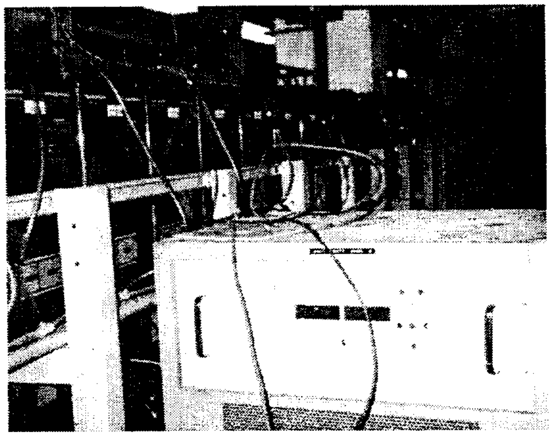

Figure 3-10. Recharging Battery Cells.

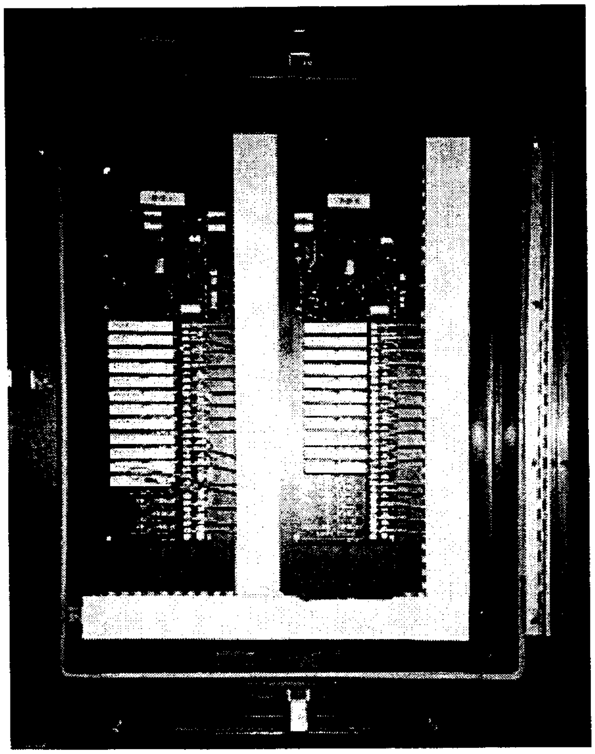

Figure 3-11. OPTO-22 Voltage Monitor.

3.4 Construction

PREPA worked closely with the general contractor who had ample experience in the construction of reinforced concrete buildings. However, the contractor's lack of experience with electric power installations prolonged the construction period even though PREPA operations and maintenance (O&M) personnel were present throughout construction. The participation of key team members enabled several beneficial changes to building design during construction. Nonetheless, more proactive participation by the battery vendor and architect/engineer would have facilitated construction and acceptance testing.

Bring all suppliers together to review system impacts. In the integrator role, PREPA worked extensively with each supplier. However, PREPA never brought all the awarded contractors and vendors together. Nor did the vendors take the initiative to review what was being done by PREPA that would impact their equipment. When the battery vendor visited PREPA in June 1994 during initial testing, they first learned about the engineer's design to power the OPTO-22 voltage sensors off of the same batteries as were being monitored (see Figure 3-11). UE&C had the same design at Chino, where only pilot cells were monitored. At PREPA, all 6,000 cells were monitored, but only 864 cells provided power to the monitor system. The OPTO-22 monitors drained the 864 tapped cells significantly, introducing voltage imbalances within the strings. The battery vendor warned PREPA about the impact this would have on battery life, and the architect/engineer sought an alternative solution. The vendor loaned PREPA additional batteries to power the OPTO-22 system until two separate banks were purchased. In hindsight, an advance meeting would have been invaluable in providing an opportunity for each vendor to understand how the design and performance of the various components would impact each other. Interface issues that occur throughout any system might have been more easily resolved if important communications channels between vendors and contractors had been established.

Build time into the schedule for weather-related delays and construction errors. The builder lost 34 days of construction due to heavy rain between 11/2/92 and 1/22/93. There were issues concerning concrete strength in columns that required re-testing. As in all large jobs, architectural drawings were misinterpreted and equipment could not be installed when it arrived. For instance, the motor control center could not be installed in the PCS room as a result of an error in locating the electric inlet cables under the concrete floor (see Figure 3-12). The inlets were only 5" off, but it required breaking open the concrete floor and moving the cables 5" forward so the cabinet could be positioned.

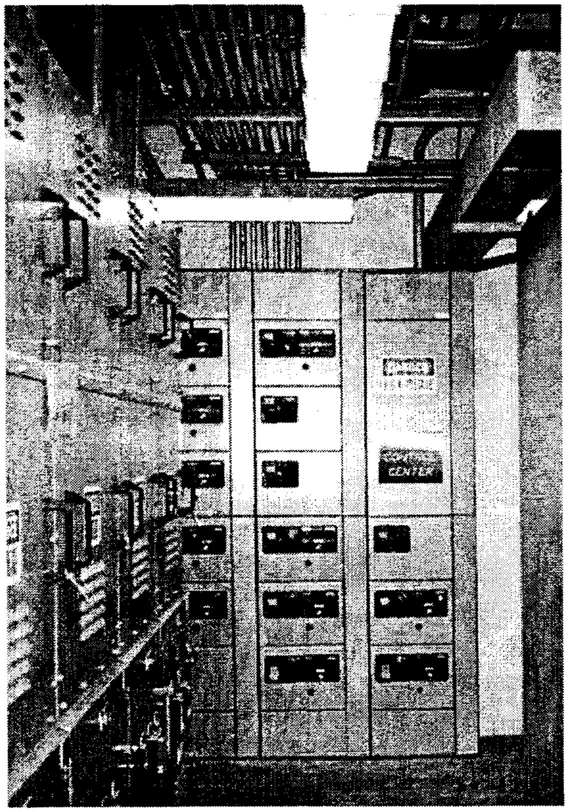

Figure 3-12. Motor Control Center.

Ensure that general contractors use qualified subcontractors for specialized work. PREPA was required by statute to sign contracts with the lowest evaluated bidders. Each supplier offered slightly different subsystems and equipment configurations, making same-basis comparisons of bids very difficult. A local general contractor won the building construction award on the basis of lowest bid even though they had no prior experience with electrical plant construction. Subcontractors were brought in to handle tasks that the general contractor could not perform: installation of the main power transformer and air bubbling system, and acceptance testing of key equipment. The subcontractor who installed the battery electrolyte agitation system broke off many plastic restrictor valves from the manifold piping. During installation of new valves, on-site drilling of holes and gluing of the pipes contaminated the air supply lines with plastic shavings and glue. In the end, building completion was held up a number of months due to builder miscalculations and construction problems.

3.5 Initial Start-Up

After inauguration of the BESS in July 1994, PREPA experienced a frustrating shake-out period. The system failed frequently, and it took months for the team to pinpoint the causes of failure. Likewise, domino effects further complicated the isolation of problems in component design and operation. PREPA staff were able to resolve these initial start-up problems due to their involvement in all phases of the project.

Verify control software for battery management. The battery-charging algorithm used at start-up was incorrect. These problems were not identified until March 1995. There was a drought on the island that winter, which limited the use of PREPA's hydro units and the availability of boiler make-up water at various steam plants that controlled frequency. During those five months, the BESS continuously received a trickle charge and was used heavily for frequency control. Only four rapid discharges occurred through mid-March and the BESS was probably not fully charged immediately following each rapid discharge. However, refresh charges were applied weekly and equalization charges did occur as needed. Communications between PREPA and the battery vendor were not sufficiently thorough to resolve the fine details in the logic of the three charging modes during system start-up. The vendor's charging guidelines called for maintaining an initial current limit and tapering the current once a voltage limit was reached. To end the charge, the guidelines specified counting the amp-hours into the battery up to 104% of the estimated rated capacity. The criteria proved insufficient to determine a fully charged state. The problem was compounded by inaccuracies in the calculation of state-of-charge. The consequence of this was that the charging logic did not provide proper charging. This situation may have contributed to the 71 cell failures observed in 1995.

Monitor all systems for unanticipated problems. The method originally used to measure DC bus voltage (using a voltage divider with 300-ohm resistors) generated 2 kW of heat inside each breaker cabinet. Temperatures inside the cabinets approached 150°F. This temperature could have seriously damaged the isolators, transducers, and voltage and current meters in the cabinets. PREPA quickly identified the problem and a possible solution. The DC switchgear contractor, PACS, agreed with PREPA's solution and changed out the resistors (replaced with 3,000 ohm), which reduced heat dissipation in the cabinets to a tolerable level of 150 watts.

Install appropriate ground detection equipment. Safety equipment was designed into the BESS, however, not all systems operated according to specifications. The ground detection system supplied by the DC switchgear vendor operated erratically and resulted in countless nuisance trips (see Figure 3-13). It caused false alarms that PREPA wasted valuable man-hours to address and eventually learned to ignore. PREPA has had poor experience with the ground detection system on its standby batteries as well. This "safety" system has not performed as expected, and represented an extra capital and O&M cost with no perceived benefit.

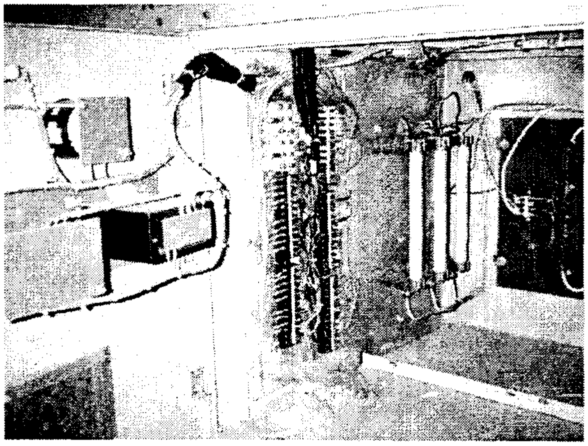

Figure 3-13. Inside DC Switchgear Cabinet.

Interface the BESS with central utility dispatch operations. PREPA is pleased with the first-of-a-kind facility interface it designed and implemented. Essentially a micro-SCADA, the BESS control system interfaces with the utility-wide SCADA system at the Operations Control Center in Monacillos, Puerto Rico (see Figure 3-14). The two SCADA systems have worked well together ever since the first system trip triggered an automatic BESS response to mitigate a load-shedding event in November 1994.

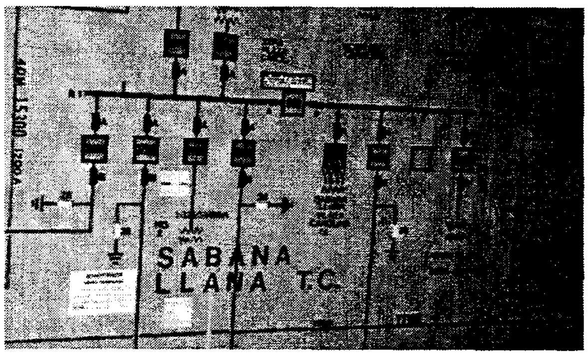

Figure 3-14. SCADA Control of the Substation and BESS.

Access design and construction staff as needed to resolve start-up issues. PREPA had continuous access to General Electric when attempting to resolve the issues impacting PCS performance. Two PCSs are located on the first floor but each controls a separate floor of batteries. During the first five months following plant inauguration, the PCSs tripped on innumerable occasions, preventing the BESS from operating continuously. GE assigned personnel on a permanent basis on-site to monitor the PCS. Other experts supported the effort to resolve problems as they were identified. Various causes were found and corrected, including defective electronics cards, a noise signal interference, and incorrect operation of a fault protection circuit (see Figure 3-15. The PCS malfunctioned during operational testing, resulting in several hundred thousand dollars in costs covered by the vendor.

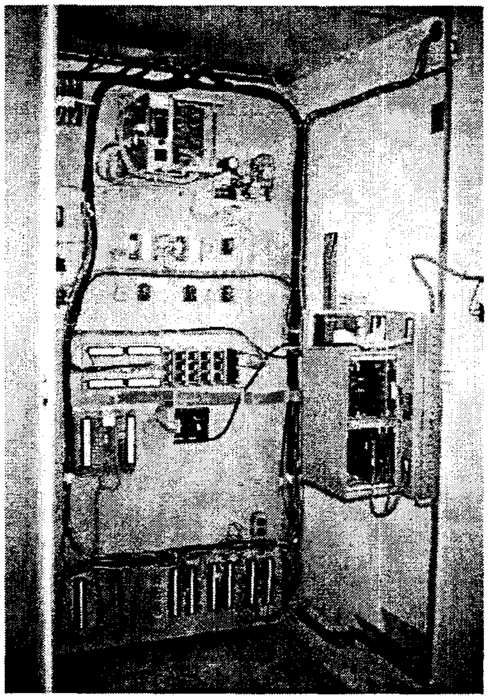

Figure 3-15. Inside PCS Cabinet.

Allow for long start-up period for one-of-kind projects. PREPA was determined not to build a first-of-a-kind demonstration of novel technologies. Nonetheless, few of the components were off-the-shelf and, in the end, PREPA became the owner of a one-of-a kind system that required more staff attention than originally anticipated. There is no one standard size for power and energy output from large BESS installations built to date. The transition problems from initial start-up to full operation varied with the component. The PCS took a few years before it passed all of the required acceptance tests, and other subsystems moved at various paces into operations. As a point of reference, a combined cycle power plant takes one-to-two years in the initial start-up phase.

3.6 Operations

Continuity in PREPA's BESS team facilitated the transition from initial start-up to full operations. One team member, who had been involved with the facility since the construction phase, continued as the plant manager through 1997. Unique problems in system operations were solved during the first two years of operation. PREPA staff made many modifications that improved BESS performance.

Coordinate smooth turnovers with all participants. The engineer in the Construction Division at PREPA turned over the plant to the Operations Division in 1996, two years after the plant was inaugurated. The Operations Division did not initially accept the BESS and required changes and corrections to the PCS and other subsystems. For example, they did not want to be assessed the charge for installing an air conditioning system. Negotiating turnover criteria well before the expected turnover date would have eased the transition for PREPA.

Maintain trend data on BESS responsiveness. PREPA has not made a continuous effort to trend data on outages. PREPA's Transmission Planning Department maintains a table of load shedding events, with information on battery discharge from the Dynamic System Monitor (DSM) at the plant (see Figure 3-16). The BESS technicians cannot access the DSM even though it has a keyboard and screen and is located in the FCS room. The DSM monitors frequency and battery output in MWh and MVARs during low-frequency and rapid discharge events. The DSM records a maximum of 120 seconds for each event. No other report documents battery operations to prevent load-shedding events or to provide frequency regulation. There is no report on BESS up-time. There is a daily report on availability for all generation plants at 6 AM, which reports whether the plant is running, and the quantity of available output. The data on the plant that has not been logged or trended is now unavailable to others who could use it to design improved systems.

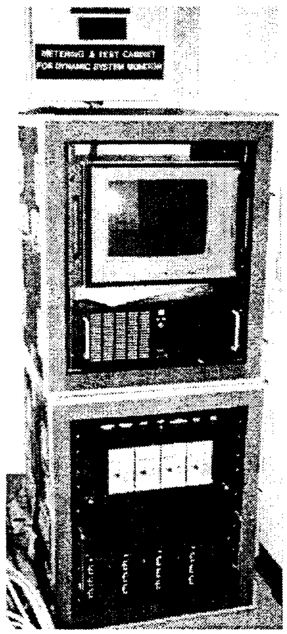

Figure 3-16. Dynamic System Monitor.

Improve operations by addressing engineering details. Current monitoring of cells is very useful for calculating state-of-charge to control subsequent recharging. With the existing 50-millivolt shunts in the DC switchgear transducer, however, PREPA cannot obtain precision in reading current. PREPA plans to install new 200-millivolt shunts, which will improve precision in current readings and state-of-charge calculations. Ideally, specific gravity and final current are needed to calculate true state-of-charge, but it is impractical to measure specific gravity on all cells. By paying attention to engineering details in subsystems, such as the DC switchgear, PREPA can improve overall system performance.

Choose upgradable, non-proprietary electronics and data systems. The BESS data acquisition/archiving system is already obsolete (see Figure 3-17). In 1991 when PREPA solicited bids for the FCS, 200-MB hard disks and optical disk readers were considered state-of-the-art and custom-designed software was the norm. The Leeds & Northrup's MAX 1000 system has two major flaws: it is very difficult to modify the control logic and it is impossible to export data into other software programs for analysis. PREPA can change a few parameters in the Applications Processor, but it cannot change the control loop without help from the programming subcontractor ACS. While initial costs would have been higher with more sophisticated hardware and software, PREPA would have avoided costly visits from the programming contractor. New data

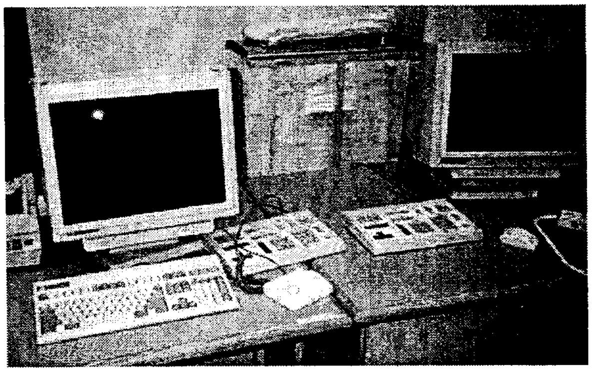

Figure 3-17. Control Room Data Monitoring System.

management systems installed at PREPA permit operator changes to control loops, archive storage, and retrieval using commercial programs like Oracle. The optical reader disks in the MAX 1000 are very expensive and not transferable among other computers. Without readable electronic media, the BESS operators depend on reports issued from three printers. The Daily Report provides an hour-by-hour summary of BESS operation in rapid discharge, frequency control, and voltage regulation mode. The Cycling Report for frequency control counts the cycling export and import current each day and reports the depth of discharge and length of cycle for each floor. The OPTO Voltage Readings provide as-needed bar graphs of voltage levels for each 4-cell group. Data in this form is not easily analyzed or studied for long-term trends.

Implement fully debugged data tracking. Data tracking and record keeping are not sufficient at the BESS. PREPA and the programming contractor had difficulty deciding which data was useful to read and keep for statistical purposes. The original optical reader tracked MW, VARS, state of charge, and frequency over 15-day periods. PREPA had problems with the optical reader, which conflicted with the control system and would occasionally erase the hard drive. PREPA disabled the system in 1996 and has never implemented an alternative record keeping system.

Identify root cause of excessive cell failures. Early in 1995, following a deep discharge of the battery, 71 cells failed. The cause was attributed to inadequate charging, leading to excessive discharge of weak cells. After this event, the control logic was modified to ensure a full charge and a more accurate calculation of state-of-charge. PREPA had originally purchased 30 replacement cells from the vendor anticipating a failure rate of 0.5%. By early 1998, it became evident that cells were failing at a much higher rate. By September 1998, over 300 cells or 5% had failed and by December 1998, an additional 600 cells needed to be replaced. Without sufficient replacement cells on hand, PREPA began to use good cells from string 4 on the second floor to replace all failed cells in the remaining five strings (see Figure 3-18). The typical failure mechanism is growth of the positive plate that causes shorts between positive plate grids and negative plate lugs. One explanation for the failures is that the initial problem with the control system charging logic "weakened" all the cells. However, upon closer examination, it has been found that out of the 100 replacement cells not subjected to this initial charge problem, about 15 have failed due to plate growth. This represents a failure rate of 15%, similar to that experienced by the entire cell population at the BESS. As of April 1999, PREPA and the battery vendor continued to negotiate corrective actions. PREPA believes that an issue to be resolved is the appropriateness of the cell design for the intended application. As a result of these cell failures, the BESS is not currently used in frequency control mode, as this seems to exacerbate the failures.

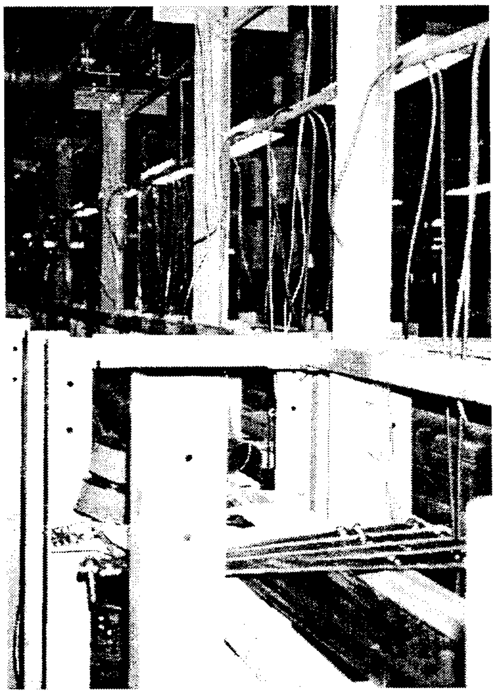

Figure 3-18. Empty Racks Remain on String 4.

3.7 Maintenance

Battery cell failures and replacement have been the biggest maintenance issues. Building logistics aggravate this situation (rack design, no elevator to second floor, and limited heavy equipment handling capability). The smallest BESS outage possible to replace a few localized cells is one string, which occupies one-third of one floor (one string is comprised of three rows). Figure 3-7 (on page 18) shows one such row. Typically, an entire floor must be taken out of service, leaving only 10 MW available for load shedding avoidance. The time and effort required to change out cells is significant and costly. Three men can remove and replace a maximum of 16 cells in a day (see Figures 3-19, 3-20 and 3-21). One of the biggest problems is rack design, which provides no clearance between the rack and the cell jars to permit the use of a forklift. The BESS battery technician designed a sling that was successfully used to remove good cells. A V-shaped forklift was also designed to permit removal of good cells from the bottom rack.

Establish appropriate warranty conditions. PREPA has had warranty issues with its vendors. The battery warranty went into effect once PREPA first applied a charge. The batteries have completed five out of ten years on their warranty, even though the BESS has only operated four years. The cell failure rate has accelerated and PREPA is concerned that cell life is closer to five years than the ten years requested in the RFP. The premature and accelerated failures are causing extraordinary maintenance costs. The BESS plant manager must borrow men from other facilities to handle the cell removal and replacement process. Replacing the 600 cells that failed between September and December 1998 will require two months of continuous work by a minimum of three men (see Figure 3-22).

Acquire tools appropriate for maintenance. Every year PREPA staff must retorque all the clamp lugs on the batteries. There are eight lugs per cell, for a total of 48,000 lugs. PREPA has accomplished this task three times so far. Air torque wrenches were not originally specified, but should have been purchased. Another purchase should have been an infrared temperature scanner because automated temperature monitoring for every cell is not economical or practical. The BESS plant manager hopes to borrow the infrared scanner from the transmission linemen in the district to facilitate quicker checking for hot spots at regular intervals. The plant does have a heat tracer to measure temperature at the jar and temperature sensors in the battery rooms trigger fans when the inside temperature rises 5°F above the outside

Figure 3-19. Disconnecting Cells.

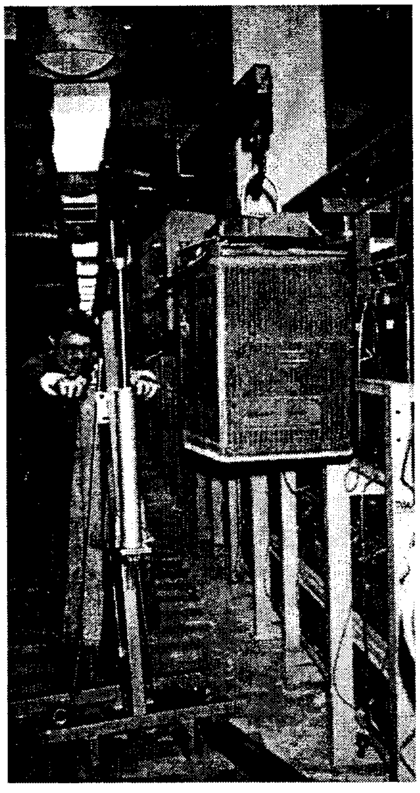

Figure 3-20. Removing Failed Cell.

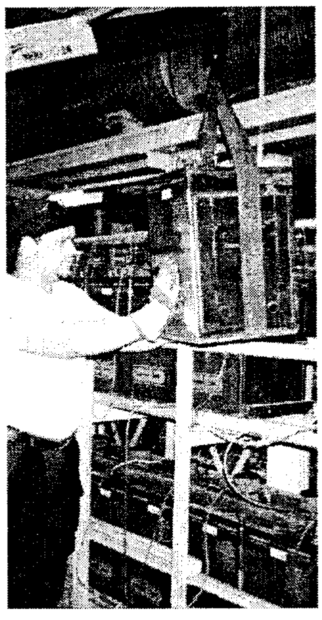

Figure 3-21. Dropping In Good Cell.

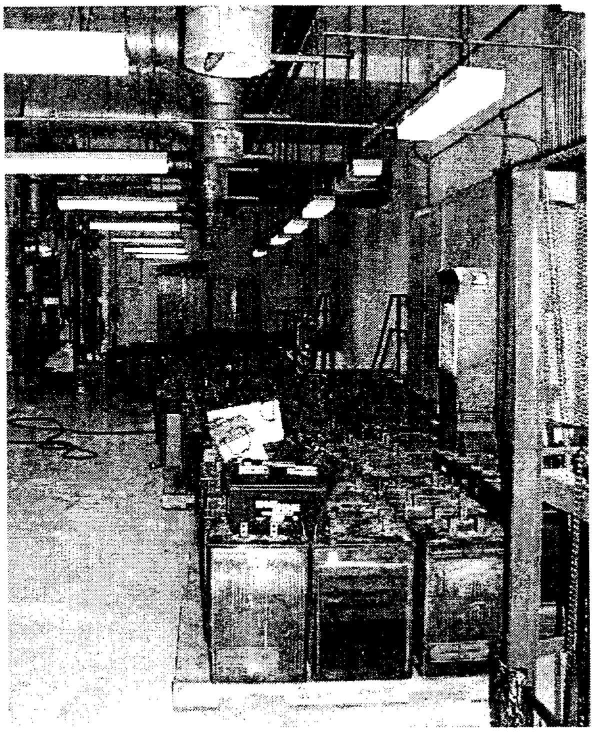

Figure 3-22. Failed Cells on Second Floor.

temperature. These additional, unanticipated O&M purchases should be made.

Install equipment to facilitate maintenance and safeguard personnel. In many cases, subsystems of the plant experienced initial problems and PREPA engineers had to modify the system design or maintenance procedures. For instance, to keep the automated electrolyte agitation system clear, PREPA staff had to cut the pipe end and introduce an adapter with a removable cap at the ends of the air bubbling system. Pipes could then be bled to remove dust and other foreign matter. To perform maintenance on the cells, PREPA staff open the isolation switches and remove jumpers to avoid the 400 volts still in the system. Staff take safety precautions, such as using rubber gloves, glasses, and rubber boots. They need to be particularly careful when applying special reconditioning charges to several weak cells spread through more than one row. PREPA's creative problem solving has improved maintenance procedures.

Have realistic staffing expectations. The BESS was to be manned by two part-time staff – a battery electrician and instrument technician who would be shared with other distributed generation facilities. In reality three-to-four people have been staffing the facility, full-time, from the start. The difference in O&M costs from the original guidelines provided by the battery vendor is significant. This level of manpower is not much different from a small combustion turbine plant, which is staffed by two or three people. There are also unanticipated man-hours for specific tasks, such as operating the cell watering system, which was never able to operate automatically (see Figure 3-23). The solenoid valves sometimes get stuck, allowing electrolyte to overflow from the cells. PREPA staff now water the cells semi-automatically. One person starts the pump from the control room and opens each solenoid valve, communicating by walkie-talkie with two others who visually inspect the filling in the battery room. PREPA must equalize the charge in the cells before refilling with water. PREPA did not plan for this charge cycle or the additional labor needed. Current practices dictate that large battery systems will require a maintenance staff.

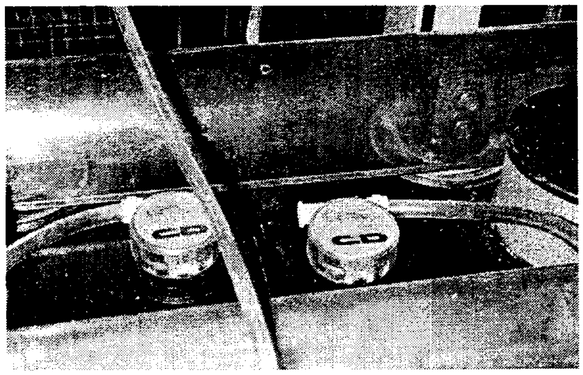

Figure 3-23. Water Inlet Atop Battery.

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4. Summary

PREPA and the architect/engineer, contractors, and vendors involved in the BESS learned many valuable lessons during every phase of the project. The lessons learned are summarized by project phase to assist PREPA and other utilities considering large energy storage systems.

4.1 Planning

- Establish a team to follow the project through completion.
- Identify up front who's responsible for the system within the organization throughout all project phases.
- Determine project responsibilities for all participants before going to procurement.
- Coordinate meetings with licensing boards to facilitate the permitting process.
- Gather and evaluate as much performance data on other facilities as possible.

4.2 Design/Engineering

- Select the architect/engineer with the most relevant experience.
- Be an active participant in system design.
- Accept that project phases are intertwined in large competitive solicitations.
- Verify available infrastructure before preparing an appropriate design.
- Identify and design for site-specific environmental and climatic conditions.
- Design the building to facilitate regular maintenance and major overhauls.
- Consider the performance and cost implications of subsystem design and configuration

4.3 Procurement

- Dedicate a purchaser in the organization to ensure good communications and project continuity.
- Budget for cost variations.
- Insure that all potential bidders are invited.
- Design specifications that avoid multiple interpretations.
- Develop contingency plans for off-schedule equipment deliveries.

4.4 Construction

- Bring all suppliers together to review system impacts.
- Build time into the schedule for weather-related delays and construction errors.
- Insure that general contractors use qualified subcontractors for specialized work.

4.5 Initial Start-up

- Verify control software for battery management.
- Monitor all systems for unanticipated problems.
- Install appropriate ground detection equipment.
- Interface the BESS with central utility dispatch operations.
- Access design and construction staff as needed to resolve start-up issues.
- Allow for a long start-up period for one-of-a-kind projects.

4.6 Operations

- Coordinate smooth turnovers with all participants.
- Maintain trend data on BESS responsiveness.
- Improve operations by addressing engineering details.
- Choose upgradable, non-proprietary electronics and data systems.
- Implement fully debugged data tracking.
- Identify root cause of excessive cell failures.

4.7 Maintenance

- Establish appropriate warranty conditions.
- Acquire tools appropriate for maintenance.
- Install equipment to facilitate maintenance and safeguard personnel.
- Have realistic staffing expectations.

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5. Recommendations and Conclusions

In addition to the 36 lessons learned that have been presented in this report, a few recommendations and comments are offered to improve existing and guide future projects.

Replace the data acquisition system. The existing data trending system has not proven to be reliable or user-friendly. The inability to transfer data to other media prevents data analysis and trending. In addition, the data acquisition system never interfaced properly with the facility control system, and software incompatibilities compromised the system until it was disabled. PREPA and the programming contractor cannot correct these deficiencies without replacing the program entirely. PREPA and its programming contractor must also come to an agreement regarding selection of data for storing and appropriate time intervals for data recording.

Consider distributed storage systems to improve a utility's competitive position. Electric utility restructuring is slowly arriving to Puerto Rico. Non-utility generators with rapid reserve will make inroads into PREPA's customer base and income. Each hurricane season, PREPA runs the risk of losing some part of its T&D network to storms. Installing a second BESS at the Sabana Llana substation will greatly increase the utility's rapid response arsenal and ability to provide clean, high-quality power with fewer load-shedding events. PREPA's Governing Board originally approved a plan for 100 MW of distributed energy storage. Following that plan will strengthen the utility's competitive position during and after industry restructuring.

Document the project history in a separate report. Since the project began in 1989, there have been many changes in staff at PREPA and the architect/engineer, vendors, and contractors. No one office maintains a complete file on the project. Corporate memory should be documented so that the next team can design, procure, install, and operate another BESS with fewer delays and problems. A project history report will become the reference guide for the next BESS team. Other facilities prepare similar reports, e.g., EPRI published two reports on Chino Battery Energy Storage Power Plant: Engineer-of-Record Report and First Year of Operation.

Consider building a small prototype of the system to prove performance, interface, and maintenance procedures. There is a variety of different battery cell types and configurations that can be used for a system of this type. One suggestion for future projects is to build a small prototype or scale model in order to gain experience with the control system, maintenance procedures, and initial performance tests. PREPA engineers could test key control system algorithms for their ability to recharge the cells correctly and measure the battery state-of-charge. The prototype could also be used to establish appropriate maintenance procedures, test rack design, and identify needed equipment to facilitate maintenance. The benefits derived from this concept must be balanced against the added cost of building the prototype and the delays in schedule for construction of the full-scale plant.

Accurately measure and control battery state-of-charge. In all large battery systems, accounting for the true state-of-charge of the battery, and especially for individual cells, is a very difficult task. It involves accurate measurements to be taken at multiple points and sophisticated software and control systems to interrupt and act on that information. It requires the integration of the cell requirements (specific to a given cell type and usage), the facility control system, the control system software, and the actual use of the BESS by the utility. If individual cells are not kept at a uniform state-of-charge, battery life and performance can be seriously affected. After much work, the PREPA monitoring system performs adequately. In future projects, this area deserves considerable attention.

In conclusion, the BESS is working and contributing in a way no other generation asset can. The system was originally designed to provide rapid spinning reserve, frequency control, and/or voltage regulation. The facility has successfully achieved its goal of providing all three functions. This was particularly the case in the aftermath of Hurricane Georges in 1998. Rapid discharge from the BESS continues to provide a reduction in network load shedding and in required system-wide spinning reserve that result in economic benefits for the utility. In frequency regulation mode, the BESS provides a fast response that reduces frequency deviations and provides operational flexibility during generation shortages. The

BESS in voltage regulation mode helps sustain system voltage levels, especially during peak hours, by augmenting the reactive power load. PREPA has overcome almost all of its problems and is reaping the rewards of its hard work.

6. Bibliography

Gergerich, P., Reyes, C., Ruiz, R., Torres, W., "Control System of PREPA's 20 MW BESS," Fifth International Conference: Batteries for Utility Energy Storage, July 1995.

Migliaro, M., "BESS Battery Cell Teardown," Report to PREPA, April 1998.

Ramos, R., and Reyes, C., "Operating Results of PREPA's 20 MW BESS," Fifth International Conference: Batteries for Utility Energy Storage, July 1995.

Taylor, P., Torres, W., Akhil, A., "Spinning reserve in Puerto Rico doesn't spin-it's a battery," *Electrical World*, April 1995

Torres, W., "PREPA's Battery Plant Status Update," Energy Storage Association Meeting, April 1997.

Torres, W., Sanchez, J., Ruiz, R., Román, E., "Outline of the New PREPA 20 MW Battery Facility," Fifth International Conference: Batteries for Utility Energy Storage, July 1995.

Torres, W., "Contingency Generation and Spinning Reserve Planning," Puerto Rico Electric Power Authority Planning & Environmental Protection Directorate, (internal white paper), Dec. 1989

Farber De Anda, M., Meeting Notes at PREPA, September 1-3, 1998, January 26-28, 1999, and April 25-28, 1999.

Telephone interviews with R. Struthers (UE&C) and S. Misra (C&D), Sept. 1998.

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