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Lead/acid batteries in systems to improve power quality

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Abstract

Increasing dependence on computer technology is driving needs for extremely high-quality power to prevent loss of information, material, and workers' time that represent billions of dollars annually. This cost has motivated commercial and Federal research and development of energy storage systems that detect and respond to power-quality failures in milliseconds. Electrochemical batteries are among the storage media under investigation for these systems. Battery energy storage systems that employ either flooded lead/acid or valve-regulated lead/acid battery technologies are becoming commercially available to capture a share of this emerging market. Cooperative research and development between the US Department of Energy and private industry have led to installations of lead/acid-based battery energy storage systems to improve power quality at utility and industrial sites and commercial development of fully integrated, modular battery energy storage system products for power quality. One such system by AC Battery Corporation, called the PQ2000, is installed at a test site at Pacific Gas and Electric Company (San Ramon, CA, USA) and at a customer site at Oglethorpe Power Corporation (Tucker, GA, USA). The PQ2000 employs off-the-shelf power electronics in an integrated methodology to control the factors that affect the performance and service life of production-model, low-maintenance, flooded lead/acid batteries. This system, and other members of this first generation of lead/acid-based energy storage systems, will need to compete vigorously for a share of an expanding, yet very aggressive, power quality market. © 1997 Elsevier Science S.A.

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1. Introduction — motivation for research and development activities

Increasing dependence on sophisticated computer technologies in manufacturing and information systems is driving needs for extremely high-quality power. Simultaneously, the electric utility industry is facing a worldwide trend towards restructuring and its associated pressures. In nations where computers are prevalent, voltage sags, spikes, and momentary outages that were once negligible now could cause customers that experience significant loss (of information, material, or workers' time) to change power suppliers. The Electric Power Research Institute (EPRI) estimates the annual cost of power quality (PQ) failures in the USA at US$ 400 billion [1]. Although, a productivity loss of such proportions would be troubling enough, uncertainty in the exact magnitude of the problem makes the issue even more pressing. The extent and uncertainty of the problem have motivated commercial development of PQ products; both the extent and the uncertainty of this potentially vast national cost have prompted government research and development (R&D) of technologies that address PQ issues.

2. Scope of research and development of integrated energy storage systems for power quality

Research and development is underway to expand the range of solutions to PQ problems beyond the conventional uninterruptible power supply (UPS) products. The technologies of interest include (but are not limited to) energy storage systems. For utilities to consider seriously such technology options, manufacturers must offer fully integrated systems, not a collection of discrete components. Consequently, both Federal and commercial re-

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search and development efforts are focusing on integrating systems (of storage technologies, monitors, controls, and power conversion systems (PCSs)) that detect and respond to PQ failures before they adversely affect customers' loads. In an integrated system that is, in effect, a 'black box,' to the purchaser, the kind of storage in the system is essentially irrelevant.

By contrast, the type of storage media is relevant to the systems' developers. A schematic representation of an energy storage system is shown in Fig. 1. The monitors, controls, and power conversion electronics must be appropriate to the storage media with which they work (e.g., flywheels, superconducting magnets, super-capacitors, and electrochemical batteries). The US Department of Energy's (DOE's) Energy Storage Systems (ESS) Program includes component research and development and system integration for all of the technologies mentioned. The focus of the program until mid-1995 has been advancing the electrochemical batteries and the electronics to support them in integrated systems. The studies have included flooded lead/acid, valve-regulated lead/acid (VRLA), sodium/sulfur, and zinc/bromine batteries. While sodium/sulfur and zinc/bromine technologies are in advanced stages of development, the commercially available battery energy storage systems employ either flooded lead/acid or VRLA battery technologies. An analysis conducted by the ESS Program (under the name Utility Battery Storage Systems Program) identified 13 high-value utility applications of battery energy storage [2]. The report identified PQ as one of the critical applications, and estimated the potential national benefits of installing battery energy storage systems to improve PQ at US$ 9 billion between 1995 and 2010. The technical maturity of lead/acid battery technology will almost certainly make it predominant in the near-term market for battery energy storage systems for PQ.

Battery energy storage systems that employ either flooded lead/acid or VRLA battery technologies are becoming commercially available at an excellent time to capture a share of this emerging market. At present, at least five commercial battery energy storage systems operate in utility applications in the USA; all of the systems have lead/acid batteries as their storage medium; three of these systems were installed specifically to improve PQ; all of the systems owe at least a part of their initial success to cooperative research and development between the Federal and private sectors.

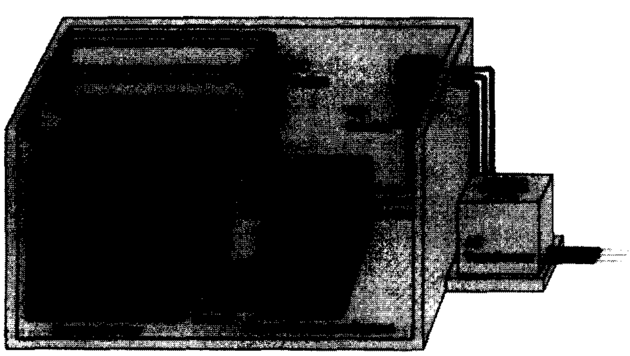

Fig. 1. Schematic of an integrated energy storage system.

3. Commercial lead/acid-based battery energy storage systems in the USA

3.1. Applications other than power quality

Crescent Rural Electric Cooperative, Statesville, NC, installed in 1987. Its system size is 500 kW/1 h, or 300 kW/2 h, or 200 kW/3 h, and its technology flooded lead/acid batteries (GNB), GTO PCS (Firing Circuits). Crescent acquired the battery energy storage system after it had undergone two years of demonstration and testing at the DOE/EPRI battery energy storage test (BEST) facility. Crescent's operation of the system has matched the utility peak about 90% of the time and has significantly reduced the associated annual peak demand charges [3].

Puerto Rico Electric Power Authority (PREPA), Sabana Llana, Puerto Rico, installed in 1995. Its system size is 20 MW/40 min, and its technology flooded lead/acid batteries (C&D), GTO PCS (GE). The Puerto Rico Electric Power Authority conducted a cost/benefit analysis to justify installation of 100 MW of battery energy storage instead of combustion turbines for spinning reserve and frequency control. During design and construction of the facility, the ESS Program conducted thermal modelling, testing and analysis to ensure that the ventilation system would be able to keep the batteries' temperature within the range recommended by the manufacturer. The utility contracted with the component manufacturers and system integrators (and performed much of the system integration) to install the first 20 MW battery energy storage system at a 115 kV substation just outside of San Juan. Many of the engineering issues that PREPA had to resolve underscored the need for fully integrated, turnkey systems to make battery energy storage attractive to utilities and their customers [4]. Since it began operation in July 1995, the facility has exceeded all expectations and PREPA has designated it as a dedicated power source. The utility is planning construction of a second battery energy storage unit before the year 2000 [5].

3.2. Power quality applications

GNB Smelter Facility, Vernon, CA, installed in 1996. Its system size is 5 MW/10 s or 3.5 MW/1 h, and its technology: VRLA batteries (GNB), GTO PCS (GE). GNB has been involved in collaborative research and development with the US DOE ESS Program in the development and engineering of valves for VRLA batteries, and in systems studies to evaluate utility benefits of installing battery energy storage; both have been fruitful. GNB and GE formed a team that combined GNB's battery expertise with GE's electronics capability. One of their first joint ventures provides GNB with a solution to an environmental compliance issue facing GNB's lead smelter. The system's primary application was to improve reliability of the power to the environmental controls for the smelter. The battery system also increases the PQ for other systems and reduces peak demand for the facility [6]. This storage system is now commercially available. GNB/GE is in the process of installing a system that is based on the same technologies for a rural electric cooperative in Alaska.

Metlakatla Power & Light, Metlakatla, AK, installed in 1996. Its system size is MW/1 h, and its technology: VRLA batteries (GNB), GTO PCS (GE). System and feasibility studies (that involve GE, GNB, the ESS Program, and Metlakatla Power & Light), indicated that a battery energy storage system could help the cooperative address the load swings and PQ problems caused by a saw mill that is a significant load on the island's electrical network. The studies also showed that the storage system would simultaneously increase the cooperative's ability to use existing hydro and diesel facilities advantageously (and help to save fuel costs associated with 55 gallon per hour consumption of diesel). The battery energy storage system will help the cooperative cope with future load growth and eventual interconnection to the mainland grid. GNB GE plans to complete construction of the system in the autumn of 1996 [7].

Oglethorpe Power Corporation, Homerville, GA, installed in 1996. Its system size is 1 MW/10 , and its technology fully integrated modules (AC Battery) that contain deep-cycle, low maintenance, lead/acid batteries (Delco), IGBT PCS (Omnion). In 1992, the ESS Program (then the Utility Battery Storage Systems Program) was working with Oglethorpe Power Corporation (OPC) to analyze the potential benefits of battery energy storage in peak-shaving and transmission and distribution (T&D) applications [8]. While OPC did not pursue battery energy storage for either peak-shaving or T&D, the analysis did provide impetus for OPC engineers to investigate with AC Battery whether a battery energy storage system with about 1 MW of power for a few seconds could cost-effectively improve PQ for an industrial customer [9]. General Motors purchased AC Battery in October 1995 [10]. AC Battery delivered a 1 MW/10 s device to OPC to improve PQ at an OPC customer site in Homerville, GA.

4. AC battery history, performance characteristics, and design features

4.1. AC battery history and products

In 1991, the US DOE formed a collaborative agreement with Omnion Power Engineering Company to develop a fully integrated, modular, turnkey, battery energy storage system for peak-load management. That agreement led to the formation of a company called AC Battery and the development of a 250 kW/167 kWh battery energy storage product, the PM250. In collaboration with Pacific Gas & Electric Company (PG&E), DOE and AC Battery placed the PM250 (shown in Fig. 2) at a test site in San Ramon, CA. At about the same time, OPC began dialog with AC Battery about battery energy storage systems for PQ. Separate from OPC, the US DOE, PG&E, and the state of Wisconsin formed a Cooperative Agreement with AC Battery to develop a 2 MW/10 s, fully integrated, modular, turnkey, battery energy storage system for improving PQ [11].

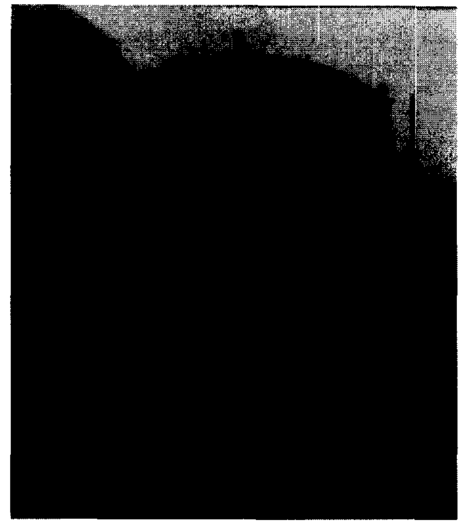

Fig. 2. AC Battery system container.

AC Battery delivered a 2 MW/10 s device to a test facility in San Ramon, CA, for demonstration at PG&E in 1996. Both PG&E and OPC are interested in the AC Battery PQ2000 system as a way to position themselves for the retail competition that Representative Mr Dan Schaefer and others in the US Senate and Congress are endorsing [12]. This legislation, called 'Power to Choose (HR3790)', would be a follow-on step to wholesale wheeling that is already underway in the electric utility industry in the USA [13].

4.2. Performance characteristics of the AC Battery PQ2000 [1]

When service voltage deviates from set thresholds, an electronic sensor in the PQ2000 transfers load from the utility to the battery energy storage system. As shown in Fig. 3, detection of a voltage disturbance and transfer of the load to the PQ2000 occurs in less than 4 ms. Ramping

[1] AC Battery relieves owners of their products of environmental regulatory compliance responsibility by accepting and recycling spent batteries. Delphi issues certificates for proper disposal of batteries removed from AC Battery units during service.

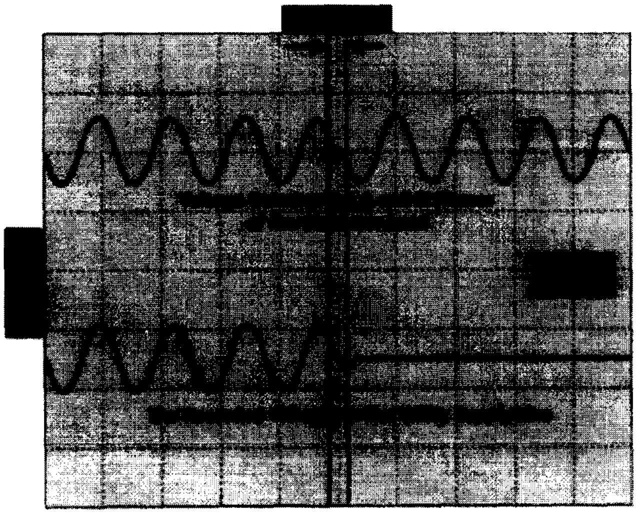

Fig. 3. PQ2000 voltage disturbance sensing and load transfer.

the output load voltage to the expected utility voltage requires less than 2 ms. The entire event occurs in less than 6 ms, but could propagate system shutdowns that cause huge losses for businesses that depend on sensitive electronic devices (semiconductor, pharmaceutical, glass, and thermoplastics manufacturers are among the many businesses for which PQ is crucial). Transfer back to the utility power occurs after the disturbance ends and the phase of the PQ2000 output is synchronous with the utility. The PQ2000's control software prevents uncontrolled transfer oscillation between the utility and battery system's power. If a power disturbance does not clear in 10 s, the PQ2000 will shut down (or can transfer critical loads to standby generation when available).

4.3. AC battery's design philosophy

The AC Battery approach is unique in that, instead of investing research and development in new battery and PCS technology, the company decided to develop an integrated approach to controlling and regulating factors that would affect battery cycle life and discharge performance, i.e., temperature, and depth, rate and number of discharge cycles, recharge methodology, and self-discharge. An outdoor system container (that houses 4 to 8 self-contained modules) replaces the 'battery room' that earlier battery energy storage systems employed (see Fig. 4). The modules are built around low-cost, high-volume production, 12 V, low-maintenance, flooded lead/acid batteries and off-the-shelf PCS components. Each module contains four trays of 12 high-power batteries (Delco 1150 — manufactured by Delphi Energy and Engine Management division of GM) and a 250 kVA bridge, inverter, and charger (manufactured by Omnion Power Engineering Company).

4.3.1. Controlling temperature to increase performance and cycle life

In ambient temperatures that range from −20 to 120°F, insulation, air-conditioning, heating, and air circulation built into the system container keep the temperature of all 48 batteries in each module to within 20 °F of their nominal operation temperature. This environment optimizes battery discharge and recharge performance and cycle life.

Fig. 4. AC Battery module with 48 lead/acid batteries and a PCS.

4.3.2. Controlling depth-of-discharge to increase cycle life

From analysis of data about the magnitude, duration, and frequency of voltage sags and spikes that electricity customers experience, AC Battery determined that a 10 s discharge at 2 MW would eliminate approximately 98% of the PQ disturbances that affect industrial and commercial facilities (see Fig. 5). A 2 MW/10 s discharge consumes only 4% of the unit's energy. As shown in Fig. 6, the batteries in the PQ2000 should have a service life in excess of 3000 cycles (about five years based on PQ data).

4.3.3. Controlling recharge regime to increase cycle life and performance

Immediately after each discharge, the modules in the PQ2000 independently, but simultaneously, initiate a patented recharge cycle (that has been optimized for the Delco 1150 battery) that limits gas evolution in the electrolyte. This process has the immediate benefit of increasing the performance of the battery by keeping the surface

Fig. 5. Voltage and duration of power disturbances relative to PQ2000 performance.

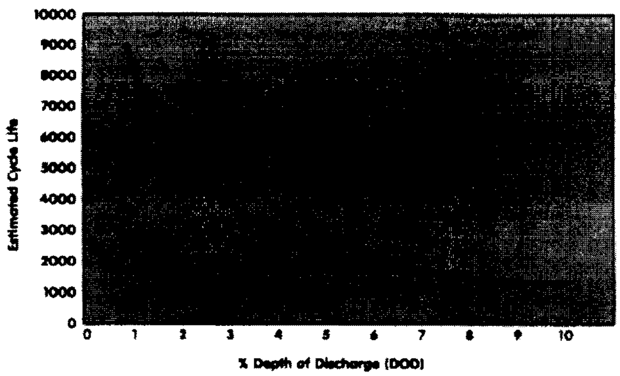

Fig. 6. Cycle life as a function of depth-of-discharge.

area of the electrode free of bubbles (and fully exposed to the electrolyte). Over time, the process also reduces oxidation of the plates (and increases performance) caused by gas at the electrode surface. Lower oxidation translates to less scale, less electrolyte stratification, and greater cycle life for the cells. Delphi reports that the process has nearly doubled the cycle life of individual batteries in laboratory tests.

4.3.4. Performing equalization charging to improve performance, service life, and life predictability

To compensate for the self-discharge that occurs in inactive lead/acid batteries, the PQ2000 applies a slight overcharge to each battery string in either of two situations: when too many hours pass between cycles, or when too few Ah are discharged. In addition to keeping the batteries ready to respond to PQ disturbances, this process seems to make battery life span more predictable.

4.3.5. Using computers to monitor and record battery string operation and predict service life

In addition to the requirement stated earlier that 'For utilities and their customers to consider seriously such technology options, manufacturers must offer fully integrated systems, not a collection of discrete components', utilities and their customers require products with known service lives and reliable warrantees. The PQ2000 incorporates a computer monitoring system that makes both of those features available. By monitoring the discharge amperage and the recharge voltage for each string of batteries, a computer can act as a 'fuel gauge' to detect and report when a battery string is nearing the end of its life. With this information, maintenance can be scheduled in advance to ensure continuous system reliability. The computer can also detect and record discharge/recharge events and create a log of service life that enables the manufacturer to offer specific warrantees on their system. With this system, AC Battery is able to include the batteries in a full, single-source warrantee for the entire system.

5. Conclusions

As dependence on computer technology and global pursuit of economic competitiveness increase, the demand for PQ will be even more pressing. The increasingly competitive electric utility environment will only increase the pressure. The market for factory-integrated PQ devices is gradually emerging. To capture a share of this market, lead/acid-based, battery energy storage systems must be commercially available. Lead/acid-based battery energy storage systems that utilize mature technology that is already in widespread commercial use have a strategic advantage in the near-term market. Fully integrated energy storage systems that use such mature technology are already economically viable and cost competitive with competing technologies for numerous PQ applications. These systems are expected to dominate the near-term market, and development and testing of energy storage systems (for PQ) with other battery chemistries are underway.

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