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Battery Energy Storage Technologies

MAX D. ANDERSON, SENIOR MEMBER, IEEE, AND DODD S. CARR

Invited Paper

Battery energy storage systems, comprising lead-acid batteries, power conversion systems, and control systems, are in commercial operation around the world. They are used by three main groups: power generating utilities; power distributing utilities; and major power consumers (such as electric furnace foundries). The principal advantages of battery energy storage systems to generating utilities include: load leveling; frequency control; spinning reserve; modular construction; convenient siting; no emissions; and investment deferral for new generation and transmission equipment. Power distributing utilities and major power consumers can avoid costly demand changes by discharging their batteries at peak periods and then recharging with lower cost off-peak power (say, at night). Battery energy storage systems are most cost effective when designed for discharge periods of less than 5 h; other systems (for example, pumped water storage) are better suited for longer discharges. It is estimated that by the year 2000 there will be a potential need for 4000 MW of battery energy storage. New construction of five plants totaling 100 MW is presently scheduled for completion by the Puerto Rico Electric Power Authority between 1992 and 1995.

I. INTRODUCTION

Lead-acid batteries offer a technically feasible, economically viable, and environmentally acceptable method of utilizing energy storage as a means of electrical load management. When combined with a power conditioning system and control circuit, the lead-acid batteries complete the essential requirements of a battery energy storage system for use by generating utilities, power distributing utilities, and major power consumers. The principal advantages of such a system of generating utilities include: spinning reserve; load following; frequency control; load leveling; dispersed siting near load centers; no emissions of air pollutants; modular construction; and deferral of investments for new generation and transmission equipment. For power distributing utilities and major power consumers, the ability to shave peak demand loads, by means of discharging stored battery energy, can offer significant economic benefits [1]. Of course, such batteries would be recharged with lower cost off-peak power (for example, at night). This paper includes discussions of lead-acid battery technology; subsystems and their interfaces; control strategies; operating systems in the United States; economic models; and the future outlook for battery energy storage.

II. TECHNOLOGY OF LEAD-ACID BATTERIES

Lead-acid batteries are electrochemical energy storage devices that may be reversibly charged and discharged many times. Each cell of a charged lead-acid battery comprises a positive electrode of lead dioxide (PbO_2) and a negative electrode of sponge lead (Pb), separated by a microporous material. When these electrodes are immersed in an aqueous sulfuric acid electrolyte, contained in a plastic case, a nominal open-circuit potential of 2 V is created. When the circuit between the two electrodes is closed, the battery discharges its stored energy; the lead dioxide on the positive electrode is reduced to lead oxide, which reacts with sulfuric acid to form lead sulfate; and the sponge lead on the negative electrode is oxidized to lead ions that react with sulfuric acid to form lead sulfate. In this way, the chemical energy stored in the battery is converted to electrical energy. Then, by means of an external source of direct current, the battery can be recharged by reversing the foregoing oxidation-reduction reactions to convert electrical energy into stored chemical energy. Several thousand charge-discharge cycles are possible with properly designed lead-acid batteries.

In general, there are three types of lead-acid battery designs: flooded electrolyte; starved electrolyte; and gelled electrolyte. In the flooded electrolyte batteries, an aqueous solution of sulfuric acid is used (specific gravity = 1.785 at end of charge; 1.170 after 80% depth of discharge, typically). The lead dioxide and sponge lead in flooded cells are supported on lead alloy grids, containing alloy additions of antimony and arsenic for increased strength and extended cycle life. For deep cells (say, 1 m tall), air-lift pumps are employed to overcome acid stratification and periodic additions of water are required (for example, every six months). Ventilation is provided from the cover to allow the escape of gases formed during the battery charging process (including hydrogen, arsine, and stibine).

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Maintenance requirements include tightening connections, cleaning cell vents and covers, checking cell temperatures, monitoring acid specific gravity, and adjustment of flame arrestors. Flooded electrolyte batteries were specified for use in the battery energy storage systems at the Chino Substation of Southern California Edison Company and at the Sabana Llana Substation of Puerto Rico Electric Power Authority.

In starved electrolyte batteries, the sulfuric acid electrolyte is completely absorbed into a highly porous separator material, which may comprise a combination of fiberglass and polyethylene. When such batteries are charged, the separator material has sufficient void space to allow passage of oxygen from the positive to the negative electrode where the oxygen recombines with hydrogen to form water. This permits starved electrolyte batteries to operate theoretically without the need to add water. Also, as the electrolyte is immobilized, such batteries can be operated in any position and there is no acid stratification. For example, such batteries can be stacked up horizontally to facilitate intercell connections in a vertical plane. Starved electrolyte batteries operate at a positive pressure (say, 3 psi), with a safety vent for release of gas if the rate of overcharge exceeds the rate of recombination of oxygen and hydrogen. This eliminates external corrosion because acid mist is no longer released. The battery grid alloys do not contain antimony. Usually, lead-calcium alloy grids are used instead. This avoids excessive hydrogen gassing on the negative electrode and eliminates the generation of toxic stibine gas during the equalization charge cycle. As a result, plant ventilation requirements are lower. For energy storage applications, starved electrolyte lead-acid batteries have been evaluated at the Argonne National Laboratory in Illinois and at the Battery Energy Storage Test Facility in New Jersey.

In gelled electrolyte batteries, the sulfuric acid electrolyte is immobilized by the addition of fumed silica. This converts the aqueous acid solution into a gel between the electrodes. As a result, gelled electrolyte batteries can be operated in any position without fear of acid leakage. By using antimony-free lead grids (usually lead-calcium alloy grids), excessive hydrogen evolution on the negative electrode is avoided. This reduces pressure buildup in the vented (valve regulated) batteries, and drying-out problems are minimized. Also, as the gelled electrolyte ages, shrinkage cracks develop and this improves the rate of migration of oxygen from the positive plates to the negative electrodes, where it recombines with hydrogen to form water. This theoretically eliminates the need to add water. Careful thermal management (for example, by forced air circulation) is important to assure that all cells are operated at essentially the same temperature, especially during recharging. Gelled electrolyte batteries have been successfully operated for several years at the battery energy storage facility in the Humboldt Foundry of Johnson Controls, Inc., in Milwaukee, Wisconsin. The company realized significant savings in electricity costs as a result of discharging their batteries when the electric melting furnaces are operated several times a day, thereby avoiding utility peak demand charges. (Economic model results are discussed later in this paper.)

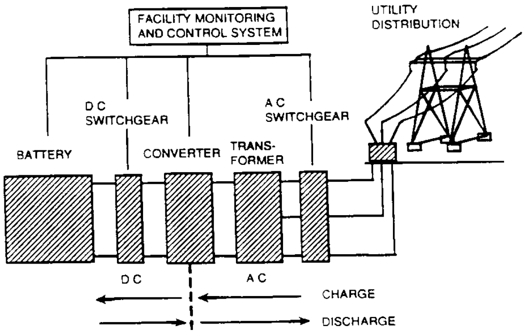

Fig. 1. Battery energy storage/conversion system (Source: AP-5845, 6–88).

III. Subsystems and Interfaces

The batteries described must interface with the electric utility through the power converter, which rectifies ac to charge the batteries, and later converts dc to ac to supply the utility load. To accomplish this, the battery energy storage (BES) system is composed of three major subsystems that have to be defined, sized, and designed or specified. They are:

- Battery subsystem.
- Power converter.
- Balance of plant (BOP).

Each of the above subsystems is developed and manufactured by a different supplier. A system integrator is required to complete the overall design, procurement, and integrate the subsystems into an operational system that meets the customer's requirements (performance and economic). In addition, adequate metering (kW, kWh, V, I) and system protection must be included. A block diagram of the system is shown in Fig. 1.

The battery subsystem is sized to satisfy the energy required (kWh) by the customer peak load for the duration of the peak load. In contrast, the power converter subsystem is sized to satisfy the peak power requirement (kW) of the load, which corresponds to the peak discharge rate of the battery. For example, the following customer loads are required to be shaved entirely by BES system:

1) 1-MW peak of 2-h duration.
2) 1-MW peak of 4-h duration.

The battery required for the 1-MW peak of 4-h duration in terms of kWh capacity is approximately twice the capacity required for the 1-MW peak of 2-h duration. However, the size of the converter in terms of kW capacity is the same for both examples. The converter is rated in kW continuous output; whereas, the battery is rated in terms of energy (kWh) capacity.

The balance of plant (BOP) is designed to provide environmentally sound housing for the battery and converter

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Table 1 Load-Leveling and Peak-Shaving Lead-Acid Battery Energy Storage Systems Operating in United States [2]

Description of energy storage system	Power (kW)	Energy (kWh)	Batteries in system	System voltage/dc (V)	Battery type	System floor space	Start-up date
Chino 10 MW substation—Southern California Edison Company, Chino, CA	10 000 (10 MW)	40 000 (40 MWh)	8256	2000	Flooded cell	48 400 ft^2 (4496 m^2)	August 1986
Advanced load management system—Keefe Avenue battery plant, Johnson Controls, Inc., Milwaukee, Wisconin	300	600	300	600	Flooded cell (40%); gelled/sealed (60%)	2000 ft^2 (186 m^2)	May 1986
Turn-key system for battery based energy management—Brass foundry, Johnson Controls Inc. Milwaukee, Wisconsin	300	580	192	384	Gelled/sealed	484 ft^2 (45 m^2)	February 1989
Battery energy storage system—Automotive battery plant, Delco Remy Division, General Motors Corporation Muncie, Indiana	300	600	1200	600	Flooded	2288 ft^2 (213 m^2)	February 1987
Peak shaving battery system—Crescent Electric Membership Corporation, Statesville, NC	500	500	324	648	Flooded	572 ft^2 (52 m^2)	July 1987

subsystems. Heating, air conditioning, auxiliary power, controls, utility system protection, and safety systems are included. For the above examples, the size of the building in square feet to house the batteries in the 1-MW peak of the 4-h duration will be larger than in the 1-MW peak in the 2-h duration, but less than double, and the cost of the BOP will be less than double. For customer applications, the size of the building will permit it to be constructed on substation property.

IV. Control Strategies

The greatest potential for BES is in multifunction applications. These include:

- Peak shaving of customer load.
- Load leveling—also benefits the electric utility.
- Energy/power for uninterruptable loads.
- Generation reserve requirement.
- Automatic generation control [area control error (ACE) requirement].
- Deferment of new generation construction.
- Deferment of new transmission construction.
- Reduction of magnetic field effects.

To obtain maximum savings for the BES user, computer based control algorithms are required. In the case of peak shaving, the potential savings is dollars per kW demand charge, where the peak demand (kW) is reset monthly. In the preceding examples, at least 1 MW must be shaved off the peak demand for the month to obtain maximum savings from the BES system. A control algorithm is required to detect the occurrence of a new peak (for the month) and discharge the battery for the time period required to shave the peak.

Some utilities are offering lower rates for allowing all or part of the customer's load to be interrupted for some relatively short period of time, even for load interruptions of 1 MW or less. The control strategy is to ensure that the batteries are charged before customer load is interrupted, and then discharged to supply the load during the time the customer is interrupted.

Time-of-day rates could provide great savings for BES users. The user should plan to serve the load with batteries during the time the rates are the highest. Battery charging would be done when the rates are the lowest.

V. Systems Operating in the United States

In recent years, several lead-acid battery load leveling systems have been installed in the United States as demonstration project to validate design, procurement, and installation costs; to demonstrate operational and economic benefits; to gain experience with operating and maintaining such systems; and to promote a new market for lead-acid battery energy storage systems. Table 1 summarizes the essential features of the five load-leveling and peak-shaving systems now operating in the United States [2]. As

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Table 2 Input Data Requirements

- System Requirements
  - Load peak power (kW), duration (hours), energy (kWh)
  - Load Profile information by month
  - Utility demand charge ($/kW)—on and off peak, by month
  - Utility energy charge (cents/kWh)—by month
  - Demand charge, energy charge escalation rates (%)
  - Capital cost escalation rate (%)
  - Discount rate (interest rate) (%)
  - Federal and state tax rates (%)
- Battery System (proposed)
  - Battery subsystem cost in $ (bid by battery supplier)
  - Battery capacity (kWh), in maximum power output (kW)
  - Battery efficiency (%), life (cycles), charge/discharge ratio
  - Battery discharge rate (kW) and minimum discharge time (h) (A family of discharge rates and times should be given by the battery supplier)
  - Battery charging rates and times required based on load profiles
- Power Converter (proposed)
  - Power converter cost (bid by the converter supplier)
  - Converter efficiency—one way (%)
- Balance-of-Plant (BOP)
  - Balance-of-plant cost (bid by the engineering/construction firm)
  - Engineering cost ($), annual O&M cost ($), insurance ($)
  - Allowance for contingencies ($)

these systems have been in continuous operation for up to five years, despite some initial start-up problems, the lead-acid battery energy storage systems have solved the energy management goals of generating utilities, power distributing utilities, and major power consumers. Moreover, in most cases, these systems have been operated in a cost-effective basis.

VI. ECONOMIC MODELS—A SURVEY OF RECENT DEVELOPMENTS

Several economic models have been developed over the last five years to assist potential users of BES in performing cost/benefit analyses [3]–[6]. Spreadsheets and other software tools are available that make the models easier to develop, more orderly in accounting for all of the variables and parameters, and easier to add to or modify the computational algorithms. The user has a simple job of filling in the blanks, and receiving an output spreadsheet that can track the costs and benefits over the number of years desired. These tools are provided by commercially available spreadsheet programs (such as Lotus 123 and QuattroPro, which are compatible with each other.)

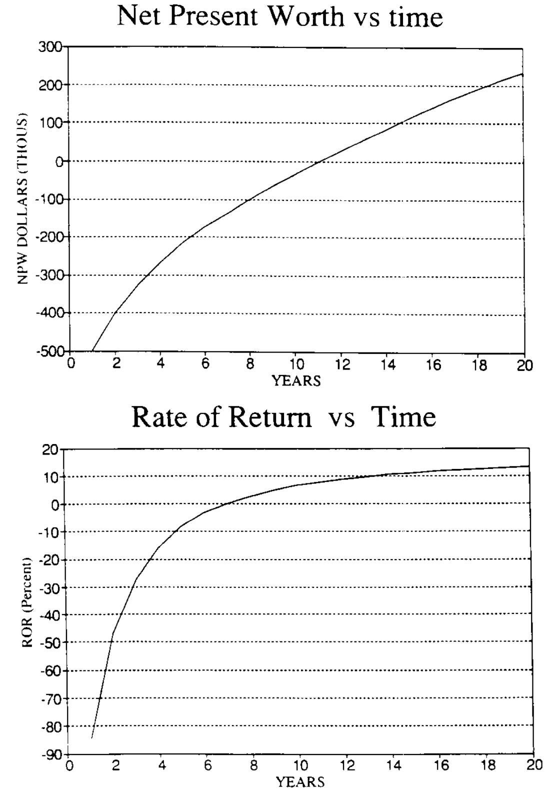

Fig. 2. Economic results.

Some of the input data that must be entered are listed in Table 2. These include the sizing requirements and cost data. Some of the economic results obtained are shown in Fig. 2; specifically graphs of net present worth and rate of return (%). In this case, the savings are in reduced demand charges ($/kW) due to shaving the peak load (kW). These economic models have been reviewed and compared by many critics. Each time that problems (errors and omissions) were found, corrections were made, and the result was an improved (more accurate) economic model. The McKinney [3] and SYSPLAN [4] models were developed about the same time period (1986–1987), but produced different economic results for what was supposedly the same input data. The differences were resolved by formalizing the basic economic relationships and using a generalized decision diagram to ensure that all the economic factors were considered and related properly [5].

By putting each of the above models [3]–[5] on the same basis with respect to accounting periods, equipment cost factors, and electrical cost savings calculations, improvements in accuracy were realized for the calculation of engineering costs, tax depreciation, demand charge savings and escalation factor, operation and maintenance (O&M), and rate of return (ROR).

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The results were compared, and the values for net present worth (NPW), return on investment (ROI), and payback period agree with 5.7%, 2.5%, and 2.5%, respectively, for all three models. This upgraded model [6] was delivered to ILZRO, along with the spreadsheet program and a users manual.

In addition to correcting errors found in previous models, the user is given more flexibility in entering cost data. Graphs of economic results can be displayed also. The spreadsheet can be used by municipal utilities, which operate under different tax rules than private customers.

The model was tested using data obtained from the Johnson Controls foundry test facility in Wisconsin and the Crescent Electric Membership Corporation [7] facility in North Carolina. Compared to analyses performed by the owners of those facilities, the model gave results for payback period within 0.1 year and ROI within 0.1% for both systems.

Spreadsheets offer the user many benefits for cost/savings analysis. These models will improve with use as the users learn to gather and evaluate the results. Modifications to spreadsheet equations (algorithms) are relatively easy to make.

VII. FUTURE OUTLOOK FOR BATTERY ENERGY STORAGE

Based upon the successful installation and operation of the five lead-acid battery energy storage systems in the United States, five such systems will be built by the Puerto Rico Electric Power Authority (PREPA) between 1992 and 1995 [8]. The first installation will be made at the Sabana Llana Substation near San Juan with a rating of 21 MW and 14 MWh. The system will serve a number of functions, including rapid reserve, frequency regulation, and voltage regulation. For rapid reserve, the system will discharge 20 MW for 15 min with subsequent ramp down to zero over the next 15 min. In frequency regulation, the battery will provide plus or minus 10 MW charge or discharge, corresponding to 0 +/− 0.1-Hz system frequency error signal. Lastly, the system will be capable of providing maximum Mvar at the facility output terminals.

The Electric Power Research Institute has estimated that by the year 2000 energy storage requirements in the United States will increase to 18 GW (18 000 MW) or about 3.5% of the total generating capacity. About 14 000 MW are expected to be provided by pumped hydroelectric plants and compressed air energy storage installations. Thus, the potential for battery energy storage in the United States is estimated to be 4000 MW by the year 2000. In addition, numerous customer-side-of-the-meter (CSOM) peak-shaving battery facilities are expected to be built to take advantage of the technical, economic, and environmental benefits derived from such facilities. A general reference on new developments is [9].

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Max D. Anderson received the BSEE and MSEE from Oklahoma State University, attended Northwestern University, and received the Ph.D. from Arizona State University.

Since 1975 he has been with the University of Missouri-Rolla, where he is now Professor of Electrical Engineering and was Director of the Power Engineering Education Program. He has published many papers in the area of power system monitoring, control, and operations. He has over 20 years of industrial and consulting experience on power system projects; such as battery storage systems, operator training simulator requirements, load management requirements, and human factors review of energy control centers. His utility experience includes requirements definition for the Union Electric Load Dispatch System, software requirements, design and testing for the Ontario Hydro DACS Control Center project, and engineering studies for Bonneville Power Administration's Dittmer Control Center. He is past Chairman of the Working Group on Operator Training (WG 78-4).

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Dodd S. Carr, photograph not available at time of publication, received the BS in chemistry in 1945 (*magna cum laude*) from Loyola College, MBA from Rutgers University in 1961, the MS in engineering from Johns Hopkins in 1948, and Doctor of Engineering degree from The Johns Hopkins University in 1950, which he received under a fellowship from the International Nickel Company.

As Manager of chemistry, electrochemistry, and patents from the International Lead Zinc Research Organization, Inc. (ILZRO), he was responsible for taking potential new uses for lead, zinc, and cadmium from concept to commercialization. He has fostered product development in such areas as asphalt antioxidants, batteries for utility load management, galvanized steel reinforcement bars in concrete, and zinc oxide weathering stabilizers in plastics. In recent years, as many traditional uses of lead diminished because of environmental restrictions, lead-acid batteries became the single largest market for lead, accounting for about two-thirds of all lead produced each year. Battery energy storage systems for electric utilities are seen as a promising new use for lead-acid batteries. In a $13 500 000 battery energy storage project for Southern California Edison Company (SCE), he managed the loan of 2000 tons of lead, in behalf of ILZRO and the lead industry to build the world's largest battery located at SCE's Chino substation in California. Prior to joining ILZRO in 1966, he held research and market development positions at International Nickel Company, Inc., Freeport Nickel Company, and Bart Manufacturing Corporation in the fields of electroplating, electroforming, and metal finishing. He is the author of numerous technical articles, has been granted many patents. He retired from ILZRO in 1991.

Dr. Carr is a member of several technical societies.

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