Journal of Power Sources, *33* (1991) 145–161

Low-maintenance, valve-regulated, lead/acid batteries in utility applications

G. M. Cook[†]
Generation and Storage Division, Electric Power Research Institute, P.O. Box 10412, Palo Alto, CA 94303 (U.S.A.)

W. C. Spindler*
Batteries Included, 15174 Kellen, Riverside, CA 92506 (U.S.A.)

Abstract

Electric power utility companies have various needs for lead/acid batteries, and also are beginning to promote customer-side-of-the meter applications for mutual benefits. Increasing use of lead/acid batteries in the future will depend heavily on improving performance and reliability of sealed, recombination designs, and on their versatility for many applications. Classifying various utility uses could be by cycling requirements, depth-of-discharge, power or energy (ratio of watts to hours), or by site (utility or customer). Deep-cycling examples are energy storage, peak-shaving and electric vehicles. Shallow-cycling examples are frequency regulation and reactive power control. Infrequent discharge examples are stationary service and spinning reserve. (Float service for telecommunications and uninterruptible power sources (UPS) applications are not addressed.) Some present and planned installations of valve-regulated lead/acid batteries are surveyed. Performance characteristics will be discussed, including recent results of testing both gel and absorptive glass mat (AGM) types of deep-cycling batteries. Recommendations for future research and development of valve-regulated cell technology are outlined, based on a recent conference organized by the United States Department of Energy (USDOE) and the Electric Power Research Institute (EPRI).

Background

The use of lead/acid batteries for energy storage by electric utility companies, and by utility customers, is being demonstrated worldwide in a wide range of storage capacities and operating modes. The basic components of a lead/acid battery energy storage system (LABESS) in a utility environment are shown in Fig. 1, and in a customer environment in Fig. 2. Operating control strategies are the principal difference in the systems and applications.

Many papers describing battery storage plants (BSPs) and applications are available in conference proceedings and publications [1–6]. A series of brief articles [7] provide timely information on energy storage applications and approaches. Examples of utility installations are summarized in Table 1,

---

[†]Deceased.

*Author to whom correspondence should be addressed.

0378-7753/91/$3.50

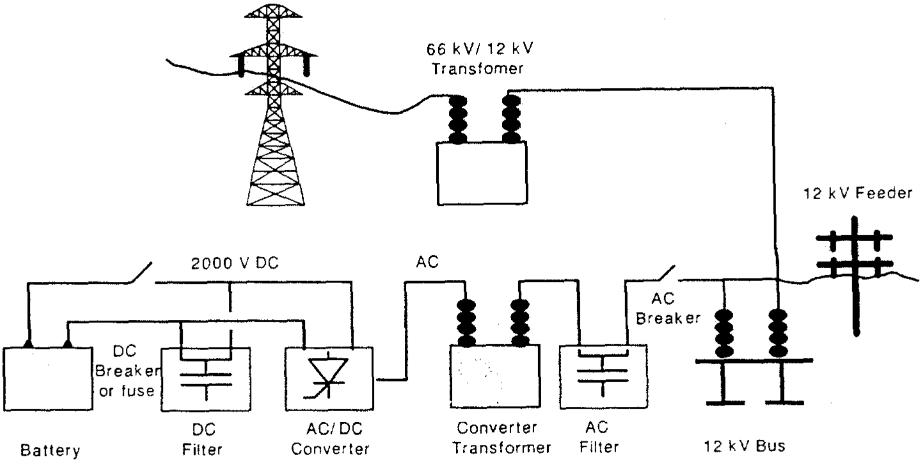

Fig. 1. Schematic of electric utility battery energy storage system.

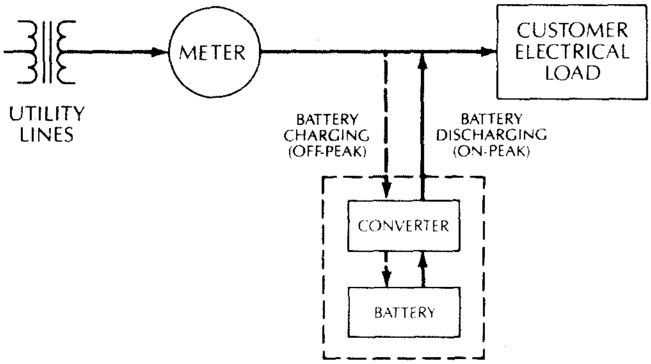

Fig. 2. Schematic of customer-owned battery energy storage system.

TABLE 1

Lead/acid battery energy storage systems in operation by electric power generating utilities

Company	Size	In service	Application
Berliner Kraft und Licht (BEWAG)-AG Berlin, F.R.G.	17 MW 14 MW h	1986	frequency regulation and spinning reserve
Kansai Electric Power Co., Ltd. Tatsumi, Japan	1 MW 4 MW h	1986	demonstration[a]
Southern California Edison Co., Chino, CA, U.S.A.	10 MW 40 MW h	1988	demonstration[a]

[a] Multi-purpose test program. See examples in Table 3.

TABLE 2

Lead/acid battery energy storage systems in operation by customers

Company	Size	In service	Application
Elektrizitatswerk Hammermuhle[a] Selters, F.R.G.	400 kW 400 kW h	1980	load levelling and peak-shaving
Hagen Batterie AG Soest, F.R.G.	500 kW 7 MW h	1986	load levelling and peak-shaving
Crescent Electric Membership Corporation[a] Statesville, NC, U.S.A.	500 kW 500 kW h	1987	load levelling and peak-shaving
Delco Remy, Division of General Motors Muncie, IN, U.S.A.	300 kW 600 kW h	1987	peak-shaving
Vaal Reefs Exploration and Mining Co. South Africa	4 MW 7 MW h	1989	peak-shaving and emergency power
Johnson Controls, Inc., Humboldt Foundry Milwaukee, WI, U.S.A.	300 kW 600 kW h	1989	peak-shaving; load levelling

[a]Secondary distribution utilities.

and customer installations in Table 2. Flooded lead/acid cells, mostly industrial/traction types for deep discharge, have been used in all systems prior to 1989. Carr [2d] has given an overview of these in utility applications, and has discussed eleven operating benefits.

Three types of lead/acid cells are now in use for energy storage: (i) conventional, excess electrolyte, vented, commonly called 'flooded'; (ii) large excess of electrolyte, commonly called 'maintenance free' (MF); (iii) no free electrolyte, pressure-relief vent, commonly called 'valve-regulated' (VRLA) or 'sealed' (SLA). The term 'low-maintenance' used in this paper excludes the 'flooded' types, but recognizes that the MF and SLA types do require occasional inspection for integrity of the components and connections.

Utilities are able to use BSPs in many different ways in addition to conventional strategies of load-levelling, load-following and peak-shaving. Table 3 [8] lists other applications that provide for special needs in transmission and distribution systems, as well as in generation. Benefits can often be achieved from multiple uses, and from indirect as well as direct sources. For example, a utility that used a BSP to replace a combustion turbine for peaking service, has obtained fuel savings, reduced air pollution, and allowed the turbine to be reclassified as an increase in generation capacity (instead of reserve) [4b].

TABLE 3

Application for battery energy storage in transmission and generating systems

Transmission/distribution systems (T/D)
1. Defer need for additional T/D capacity
2. Provide operating reserve
3. Perform reactive power compensation
4. Regulate frequency
5. Regulate voltage
6. Damp out subsynchronous oscillations and other system instabilities

Generating systems
1. Correct area control error
2. Provide ramping (up or down)
3. Provide black start
4. Provide spinning reserve
5. Reduce cycling of thermal units (reduced wear and tear)

Typical operating plants

Two of the utility BSPs with flooded cells will be briefly described for comparison with BSPs having VRLA cells. The first is located in West Berlin at the Berliner Kraft und Licht (BEWAG)-AG facility [1a, 1e, 4b, 4c]. Here, 5-cell modules of the Hagen battery are assembled in 12 battery rooms of the type shown in Fig. 3. The cells have expanded-copper negative grids, and each cell is attached to an automatic watering line to maintain the electrolyte level. Cells are also equipped for water cooling. The second utility BSP is the Edison facility at Chino [1b, 1c, 3d, 4a, 6a]. The plant consists of 6-cell modules of an Exide traction type (GL-35) that are assembled in two-tier rows in two battery rooms. There are 16 rows in each building. Figure 4 shows the assembly at the

Fig. 3. View of one battery room at BEWAG's 14-MW h battery energy storage plant in West Berlin.

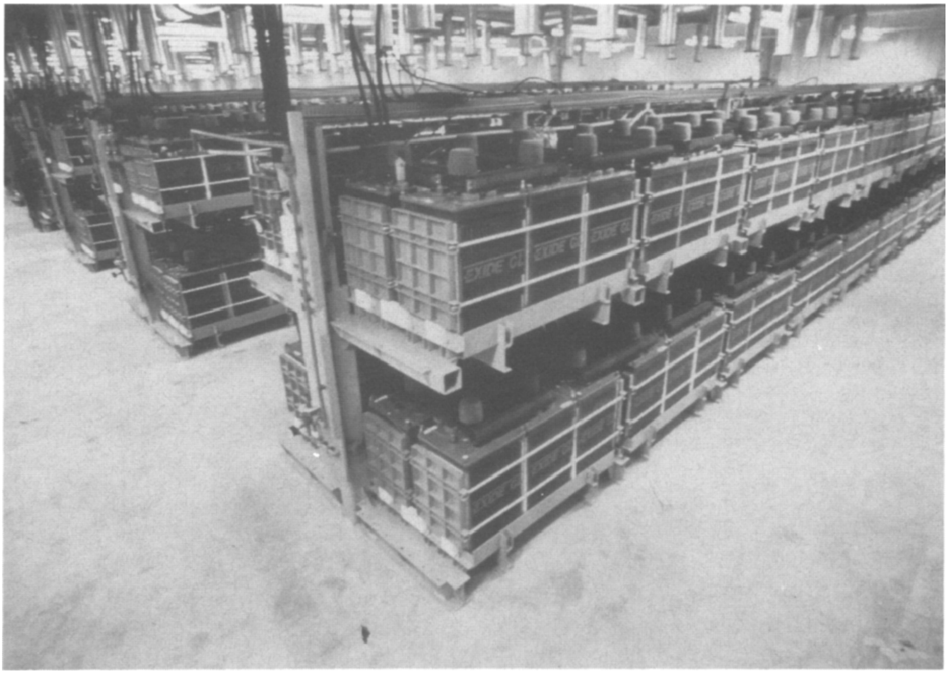

Fig. 4. View of battery rows at Edison's 40-MW h battery energy storage plant in Chino.

end of a row. Six cells on a steel pallet is the minimum removable unit for repair or replacement of individual cells.

Among the customer installations, one with flooded cells and one with MF cells will be described. The first is at Statesville [1d, 3f, 4f, 6c] where the Crescent Electric Membership Corporation (CEMC), an electricity distributor, has a GNB (Industrial Battery Co.) traction-type battery that provides

Fig. 5. View of battery energy storage plant at CEMC in Stateville.

Fig. 6. View of battery rows at Delco's 600-kW h battery energy storage plant in Muncie.

500 kW of peak-shaving service, with 500 kW h storage capacity in winter months when there is a predictable peak demand of less than 1 h duration. During the other months the BSP is operated at 200 to 300 kW for longer periods under less predictable conditions. Figure 5 shows the uncrowded, single layout in a building that also houses the converter equipment. At Muncie [4e], the Delco Remy battery manufacturing facility uses its own heavy duty MF truck batteries for peak-shaving service. Figure 6 gives an overhead view of a four-tier installation. A control algorithm manages a ramping strategy that determines daily operating power level from prior history of operation during the month. Over the first two years monthly performance averaged: 17 discharges, 25% DOD, 307 kW h, 1.27 h recharging period, 210 kV A peak reduction, and 74–84% a.c. to a.c. efficiency.

Sealed lead/acid battery storage plants

Valve-regulated lead/acid cells were first used in the 300 kW BSP built by Johnson Controls, Inc. (JCI) for a peak-shaving demonstration at their Humboldt brass foundry in Milwaukee [3e, 4d, 7g]. Operation began in Jan. 1989 using a ramping control algorithm to determine each day's operating time and power level. Battery and system characteristics are given in Table 4, and the installation is shown in Fig. 7.

Two other plants which will use VRLAs are in the planning stage and are expected to be in operation in 1991 and 1992. The details are as follows.

In San Diego, an Exide, traction-type, gelled-electrolyte battery will be installed and operated by the San Diego Gas & Electric Company (SDG&E) for a light rail transit system. The 200 kW (a.c.) battery energy storage system will serve as a prototype in one of the substations to meet peak power

TABLE 4

VRLA battery at Johnson Controls Humboldt brass foundry

Battery rating	2 h at 300 kW
Depth-of-discharge (%)	80
Discharge range (V)	380 to 320
End of charge (V)	460
GC6-1500B gel cells	192
Modules (64)	6 V, 1500 A h
Forced air cooling	4 × 1.5 HP

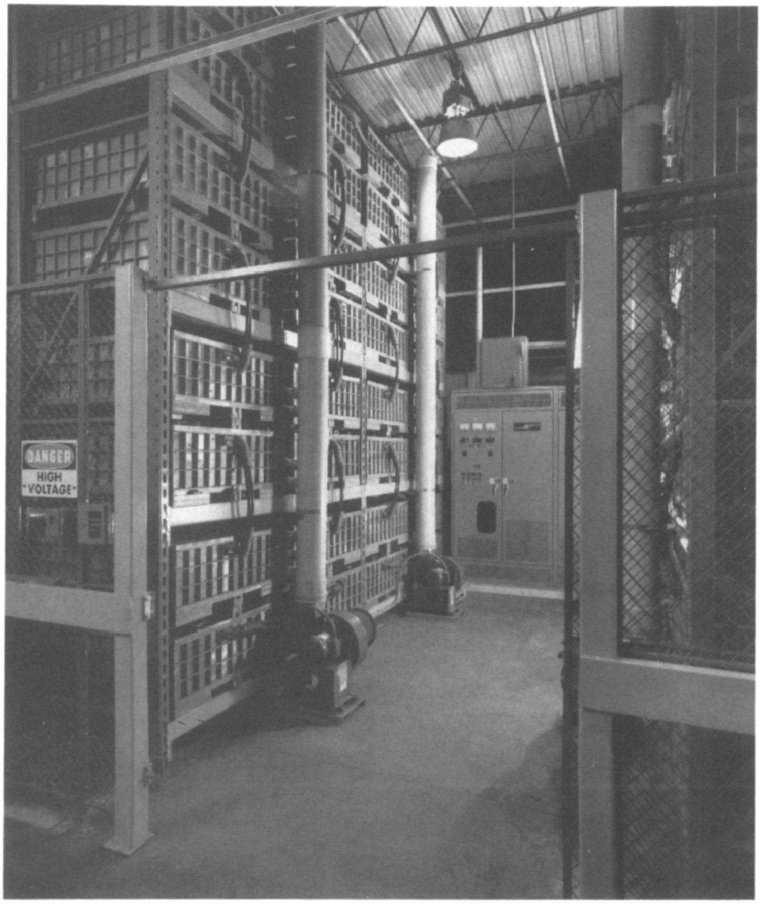

Fig. 7. View of 600-kW h battery energy storage plant at JCI's brass foundry in Milwaukee.

Fig. 8. View of GNB's sealed lead/acid battery under test at the BEST facility in Somerville.

demand during morning and evening commuter rush hours. The battery will have a 2-h capacity to 80% DOD. The cells have flat plates, low-antimony positive grids, and an 8-h rating of 1620 A h. Two cells are assembled in a steel case, to provide a stackable module similar to the GNB design shown in Fig. 8. Installation will begin in 1991 and operation before the end of the year. If operating experience and economic benefits are suitable, many other sub-stations could be similarly equipped. The design may be changed for installation on the customer-side-of-the-meter (CSOM) at the 600-V rectifier interface, rather than connected to the 12 kV utility feeder line.

At Princeton, the first example of a shared battery energy storage plant [1f] operating alternately by an electric utility and one of its customers will be installed at the Princeton Plasma Physics Laboratory (PPPL). The laboratory will use it for peak-shaving, and the Public Service Electric & Gas Company (PSE&G) will use it for spinning reserve (SR) and area regulation (AR). This will also be the largest use of VRLA batteries. The plant will be rated at 5 MW and 5 MW h, utilizing 576 12-V modules in four parallel strings of 144 modules, for a nominal 864-V interface with the a.c. to d.c. converters. The four converters will be rated at 1.35 MW and connected to the utility 13.8 kV distribution substation. PSE&G will operate the plant during hours not assigned/reserved for laboratory use. Credit for spinning reserve will be at the 5 MW power level and at ±3.6 MW for area regulation.

Module tests — gelled-electrolyte and AGM types

In mid-1988, EPRI began an effort to evaluate VRLA batteries for battery energy storage systems at utilities. The purpose of this work was to assist developers and electric utilities in understanding the performance characteristics of these batteries. In order to accomplish this task, two battery test projects were initiated by the end of 1988. The first project was designed to determine the ability of gelled-electrolyte and AGM battery types to meet the needs of various electric utility applications. The second project was intended to evaluate the impact of accelerated deep cycling on the life of these batteries.

Two specific battery types, from two manufacturers, were selected for these tests. The specifications for these two batteries are presented in Table 5. Each is rated for 1700 cycles at $\leqslant$760 A h discharge at 25 °C.

For the applications testing, a number of these modules were assembled to obtain nominal 1000-A h, 120-V battery systems (see Figs. 8 and 9). This configuration is also common for utility stationary service for switch gear operation. The applications testing [4g, 5c] was performed at the Battery Energy Storage Test (BEST) facility of PSE&G. The test system was designed to discharge the batteries in series, but to separately accommodate the recharge requirements of each.

The test program proved that the two batteries can meet the requirements of the various utility energy storage applications. Daily cycling, with long charge periods over weekends, will maintain the battery parameters within the temperature and state-of-charge operating limits specified by each manufacturer. Both batteries were easy to install and had good access for maintenance. Note that vertical stacking is a feature made possible by the fact that water addition is not required.

Thermal management of VRLA batteries is more critical than with flooded batteries because, with no free electrolyte, the former have a lower

TABLE 5

VRLA modules under test in EPRI/ILZRO program

	Manufacturer	
	GNB	JCI
Model number	85A25	LL 12-70
Electrolyte	AGM	gel
Positive grid alloy	antimony	calcium
Module configuration	3 cells in a series	15, 12-V modules in parallel
Voltage (V)	6	12
C/8 Capacity (A h)	1040	1080
Energy (kW h)	100	100
Short-circuit current (A)	8400	30000
Size (m^3)	0.122	0.605
Weight (kg)	240	510

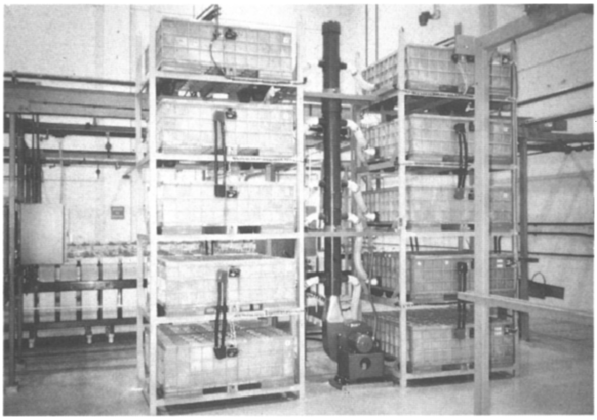

Fig. 9. View of JCI's sealed lead/acid battery under test at the BEST facility in Somerville.

thermal conductivity. Thermal cooling time constants were measured in the tests of the gelled-electrolyte and AGM batteries at the BEST facility. These can be used in modelling and design studies to improve control of performance. Following a week of continuous operation under AR cycling, and with the batteries on open circuit, the exponential cooling curves had the characteristic temperature rises and time constants shown in Table 6. The values will be somewhat dependent on differences in summer/winter weather conditions (such as humidity) and on the daily/weekly profiles of discharge/charge/idle stand/float. Temperatures of various cells in the GNB battery differed by up to 5 °C, and the cooling time constants ranged from 5 to 9 h. With only convective air flow, as originally installed, the cooling time constant was about 2 h longer.

TABLE 6

Thermal performance of VRLA battery modules

	Manufacturer	
	JCI[a]	GNB[b]
Temperature rise[c,d] (°C)		
Daily maximum	8.5	12.5
Daily average	6.5	8.5
Cooling time constant[d] (h)		
Forced	8	9
Convective (no fan)		11

[a] 0.26 kW fan.

[b] 0.12 kW fan.

[c] Above 24-h ambient average.

[d] After week of continuous area regulation operation.

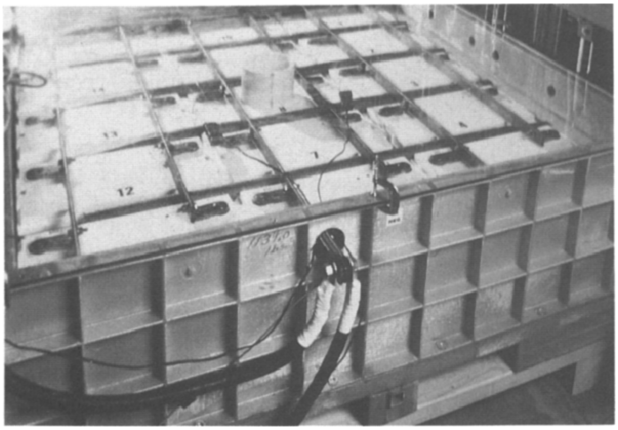

Fig. 10. View of a JCI module inner assembly of 15 parallel batteries, under test at Argonne National Laboratory.

The short-plate design of the JCI batteries permits the use of a smaller ampere-hour rated battery (Fig. 10) where high current, short discharge times are needed. As part of the testing performed at PSE&G, the discharge time to a 1.75 V/cell cut-off was determined for several discharge currents. It was found that plots of the ampere-hour capacity (C) versus the current (I) were roughly linear, with the form:

$$C = B - KI \tag{1}$$

The values for the constants (B, K) for the two batteries are as follows:

Manufacturer	Constants	
	B (A h)	K (h)
JCI	1.140	0.40
GNB	1.320	1.06

The two batteries were found to have the same capacity, 1031 A h, at a discharge time of 3.78 h. At shorter discharge times, the JCI battery had the greater capacity; while at longer discharge times, the GNB battery had the greater capacity.

Modules of the same type are being used in the deep-cycle test project at Argonne National Laboratory (ANL) [3h, 4h, 5b, 6b] under funding from both EPRI and International Lead Zinc Research Organization (ILZRO). The purpose of this project is to accelerate the failure expected to occur under cycling conditions. Since there is no accepted procedure to do accelerated cycle testing, a test procedures review committee, which included representatives of the battery manufacturers, evaluated the proposed approach. Several possible failure modes were considered and discarded as the anticipated primary mode for failure. For example, it was decided that electrolyte dry-out was an abnormal failure mode, in that it would arise primarily as a result of a valve failure or excessive over-charge.

It was finally decided that normal failure should occur as a result of failure of the active material to cycle properly. Evaluation of this failure mode requires exercising the active material to the greatest extent possible. The best stress factors to accomplish this were selected to be deep cycling (100% DOD) and high temperature (50 °C). The test matrix specified the use of four battery modules from each manufacturer with two levels of DOD and temperature being used for a total of four tests, Table 7. Discharge was chosen at the *C*/3 rate with a voltage limit that permitted either a 100% or 80% DOD. A constant end-of-discharge (EOD) voltage provides the imposition of a constant stress level to the test modules. The recharge was limited to 8 h.

TABLE 7

Accelerated life test matrix for VRLA batteries

Module number	Test temperature (°C)	DOD (%)	Assumed acceleration factor	Estimated cycles to failure	Estimated test time (months)
1	30	80	1	1200	24
2	30	100	2	600	12
3	50	80	2	600	12
4	50	100	4	300	6

TABLE 8

Preliminary results of VRLA battery acceptance and baseline performance tests

	Manufacturer	
	GNB	JCI
Model no.	85A25	LL 12-70
Average weight (kg), variation (%)	248.4, 1.6	517.5, 0.4
Capacity to 1.75 V/cell at 25 °C		
8-h Rating (A h)	1040	1080
Average (A h/W h)	1234/7297	1077/12863
Variation (%)	1.9	7.0
3-h Rating (A h)	816	954
Average (A h/W h)	947/5510	964/11450
Variation (%)	1.0	7.4
Volts at 80% DOD (V)	5.644	11.451
Variation (%)	0.3	0.4

The purpose of these cycling conditions was to maximize the number of cycles that could be achieved per unit time. At the end of life, a sampling of cells will be evaluated for the cause of failure. If the cells are operating well, that cause is expected to relate to changes that occur in the active material as a result of cycling. Preliminary test results are given in Table 8.

Other VRLA batteries for deep cycling

Peters [2a, 4j] has reported on advanced VRLA batteries specifically for energy storage applications.

Rand and Baldsing [9], and later Lambert [10], reported encouraging performance of gelled-electrolyte cells from two sources of manufacture. In tests to date, this has been equal to the best flooded types when operating under simulated remote-area power-supply (RAPS) duty. Typical use is at low rate, with deep discharge and infrequent recharge. The studies also showed that AGM cells gave considerably shorter life than their gelled-electrolyte counterparts, because of drying out. RAPS systems may use solar power with diesel generator back-up; batteries can provide optional benefits.

VRLA batteries have had the earliest and longest use in uninterruptible power supply (UPS) applications, generally for communications and computer systems emergency power. Utilities have begun to replace flooded types of lead/acid batteries in stationary service with VRLA types, in both communications and switchgear installations at generating stations and major

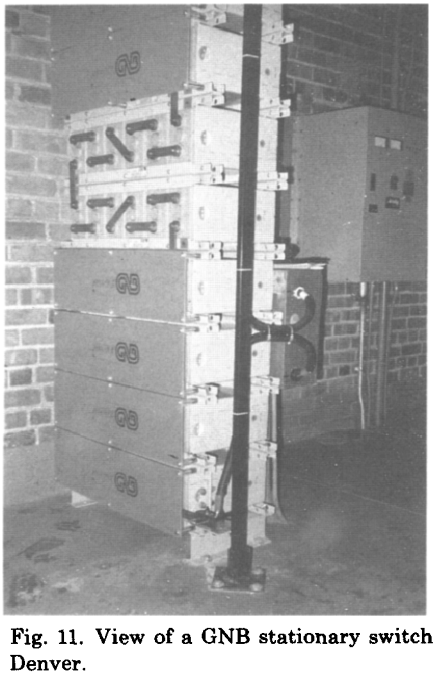

Fig. 11. View of a GNB stationary switchgear sealed lead/acid battery installed at a utility in Denver.

distribution sub-stations [3c, 4k]. At a Colorado utility sub-station, a vertically stacked VRLA battery (Fig. 11) replaced a two-tier flooded type in less than one-fourth the floor space. This is a GNB battery of the AGM type, with lead–antimony alloy positive grids and lead–calcium alloy negatives.

Hagen VRLA batteries were reported [11] to be capable of high performance in deep cycling and in stand-by applications. The cells have flat pasted plates with calcium alloy grids and AGM separators.

Sonnenschein reported on VRLA batteries in traction service [1e, 2b, 3b], with gelled-electrolyte, positive tubular plates, and calcium alloy grids. A flat plate, gelled-electrolyte battery is also being used in electric vehicle service — an application of great interest to utilities having excess generating capacity.

Monitoring the condition of lead/acid batteries has proven to be a difficult problem for utilities, especially in applications in nuclear power plants where reliable and predictable performance of batteries for emergency power is critical. A review of methods is underway and initial results were reported [3i].

Yuasa describes a 3000 A h class of VRLA battery [2c], comprising four smaller cells in parallel, having pasted plates, calcium alloy grids and AGM separators. At the $C/1$ discharge rate, the capacity of the battery exceeded a comparable flooded type by 15%. It was designed for stationary service, and its performance under deep-discharge cycling service is not yet known. Japan Storage Battery Company discussed a similar development effort [4i], and showed more than 1000 cycles in deep-discharge testing.

Johnson Controls reported [6d] on deep-discharge cycling of gelled-electrolyte batteries. Series strings of length from 6 to 30 cells, and parallel strings were found in daily cycling to have performance affected by cell construction variables such as paste density and antimony content in the positive grid alloy.

Bipolar VRLA batteries are also under development for deep cycling. It is too early to estimate their suitability for utility applications. They may, however, appear first in electric-vehicle service because of their higher power density. Deep-cycling performance was reported by Electrosource [3a] on the Horizon$^{(TM)}$ design of bipolar battery (a hybrid design). This had the novel features of co-extruded wire grids (0.5 wt.% Sn alloy), flat plates with cureless paste, and AGM separators.

For very high pulse power applications, JPL advanced [3g] a bipolar VRLA design featuring thin, lightweight pasted plates, with electrolyte absorbed in a matrix of tin oxide coated glass fibers. Additional work on this design has been published elsewhere [5a].

Recommendations

Recommendations for improving the performance of VRLA batteries, and for increasing their use in utility applications, were drawn up at a

DOE/EPRI meeting [12] that used group discussion methods to address the following three questions.

(i) How can the performance of VRLA battery systems be improved?
(ii) How can institutional and market barriers be overcome?
(iii) What specific projects must be pursued to overcome these barriers?

Low-maintenance lead/acid batteries can play a significant role in utility applications for energy storage. These will be second-generation systems, advancing the successes and experiences from the flooded cell demonstration BSPs. They will provide a much greater variety and value of investment and operating benefits than available simply from load-levelling and peak-shaving service. Environmental benefits that can be achieved by displacing the use of organic fuels in combustion turbines, and by allowing more efficient use of baseload generating equipment, are also being recognized as of a very long-term value.

EPRI envisioned these changing characteristics:

- energy management rather than storage
- distributed facilities
- multi-use systems
- joint ownership (customer/utility)
- improved reliability and stability
- service for sophisticated users

The following major actions and approaches were recommended:

- increase research and development on VRLA batteries
- perform optimized system design and applications testing
- develop products for multiple markets
- conduct multiple demonstrations

Strategies for collaborative action are listed in Table 9. It should be noted that additional support for research and development projects is being independently provided by ILZRO.

TABLE 9

DOE/EPRI collaborative leadership strategy to facilitate projects

---

Battery technology research and development (DOE)

- Pursue improved batteries through cost-shared R&D
- Continue life-cycle and performance testing of existing and new products

Battery system design, development, and demonstration (EPRI)

- Specify system requirements for components in various applications
- Accelerate integrated system designs for optimized performance
- Support demonstrations to validate technology performance and applications value

Battery storage benefits evaluation and promotion (private sector with DOE/EPRI assistance)

- Hold workshop with utility operations' staff to value the benefits of battery storage benefits
- Develop methodology, software and guide to assist utilities in evaluating battery storage benefits
- Perform market research to identify opportunities for the introduction of battery storage

---

Conclusions

New applications for large lead/acid batteries in energy storage are clearly shown in examples of existing utility and utility customer installations. A definitive future direction for new installations and a wide variety of applications can be assured if valve-regulated designs of lead/acid batteries can be significantly improved for long life under deep discharge, whether for intermittent or nearly constant use. Marketing of complete systems, such as the UPS, can be diversified to include many of the energy storage operational opportunities with electric utilities.

Although this review has not dealt with problems in the performance of VRLA batteries, there is an obvious need for manufacturers to take serious action on several fronts; for example, the following:

- tighter, optimized manufacturing procedures
- lower lifetime cost through better design, *and* matched electronic charging
- improved paste–grid interface chemistry
- shorter recharge time
- improved performance above 45 °C
- reduced weight, as with lead composite materials
- comprehensive installation and maintenance manual

UPS and other float applications, such as those needed by the generating utilities for spinning reserve (and short-term reserve power), are achievable targets for presently available VRLA batteries.

Low maintenance sealed lead/acid batteries offer an economical, efficient, and reliable means of energy storage in such electric utility applications as load-levelling, frequency regulation, reactive power control, spinning reserve and area regulation. Also, such batteries provide utility customers with means of avoiding peak demand charges in such industries as brass foundries, light rail transit systems, and non-generating electrical distribution utilities. As further improvements are made in the design, construction and operation of low-maintenance, sealed lead/acid batteries, they will find a wider range of applications by electric power utility companies as well as their customers.

References

1 *Proc. Int. Conf. Batteries for Utility Energy Storage, West Berlin, F.R.G., Nov. 9–11, 1987,* Berliner Kraft und Licht (BEWAG)-AG, Berlin, F.R.G.; Electric Power Research Institute (EPRI), Palo Alto, CA, U.S.A.; and New Energy and Industrial Technology Development Organization (NEDO), Tokyo, Japan. (a) P. Berger *et al.*, The 8.5/17 MW battery energy storage plant of BEWAG; (b) L. D. Hamlin and G. D. Rodriguez, The Chino 10 MW/40 MW h battery energy storage project; (c) A. M. Chreitzberg *et al.*, Design of a 10 MW/50 MW h lead/acid load-levelling battery; (d) B. Zickefoose, Demonstrating the technical and economic characteristics of a small battery load management system in a utility environment, (e) H. Tuphorn, Lead/acid batteries with gelled electrolyte for utility energy storage; (f) J. W. Hurwitch and D. E. Huttar, Demand-side load-levelling battery storage at the Princeton Plasma Physics Laboratory.

2 *Proc. Lead Battery Power for the 90s, Paris, France, Apr. 28–29, 1988,* Centre d'Information du Plomb (CIP), Paris, France; Lead Development Association (LDA), London, U.K.; and International Lead Zinc Research Organization (ILZRO), Inc., Research Triangle Park, NC. U.S.A. (a) K. Peters, Advances in sealed lead/acid batteries, p. 45; (b) H. Tuphorn, Sealed lead/acid batteries — technology and applications, p. 51; (c) S. Sasabe, M. Sasaki, K. Kishimoto, Y. Kasai and K. Fuchida, The development of the 3000 A h class sealed lead/acid stationary battery, p. 101; (d) D. S. Carr, Lead/acid batteries in US electrical load-levelling applications, p. 120.

3 *Proc. 3rd Int. Lead/Acid Battery Seminar, Orlando, FL, May 3–5, 1989,* ILZRO. (a) C. Morris, Development of a 12 V, 120 A h/3 h golf cart battery using co-extruded wire substrates and the Horizon battery assembly concept; (b) H. Tuphorn, Sealed lead/acid batteries for traction applications; (c) S. J. Deshpande, Performance of large strings of industrial sealed lead/acid batteries; (d) G. D. Rodriguez, Operating the world's largest lead/acid battery energy storage system; (e) G. H. Brilmyer, A turnkey system for battery based energy management; (f) B. Zickefoose, Performance of flooded lead/acid batteries in peak-shaving applications; (g) A. I. Attia, Sealed bipolar lead/acid batteries for high pulse applications; (h) W. H. DeLuca, Accelerated life evaluation of valve-regulated lead/acid batteries; (i) A. J. Salkind, Monitoring state of condition of lead/acid batteries used in utility networks.

4 *Proc. 2nd Int. Conf. Batteries for Utility Energy Storage, Newport Beach, CA, July 24–28, 1989,* EPRI, NEDO, BEWAG. (a) G. D. Rodriguez, Tests and operating results of the Chino battery energy storage project; (b) P. Berger, 30 months experiences with BEWAG's battery energy storage plant; (c) K. Krämer, Operational behavior of OCSM battery modules in BEWAG's BESP; (d) R. Hamann *et al.*, A turnkey system for battery based energy management; (e) F. S. Carothers and R. Johnston, Battery energy storage system for utility load-levelling in an automotive battery plant; (f) R. B. Sloan, Operating history of a 500 kW lead/acid battery system; (g) G. Grefe, Evaluation of two stacked valve-regulated batteries for utility cycling application; (h) W. DeLuca, Life evaluation of valve-regulated lead/acid batteries for load-levelling applications; (i) M. Iwata *et al.*, Large capacity sealed lead/acid battery; (j) K. Peters, Operational features of sealed lead/acid batteries in energy management applications; (k) B. Peticolas, Application of UPS technology in load-levelling applications.

5 *Ext. Abstr., 9th Battery and Electrochemical Contractors' Conf., Alexandria, Nov., 12–16, 1989,* U.S. Department of Energy, U.S.A. (a) T. J. Clough and R. L. Scheffler, Bipolar lead/acid battery development; (b) W. H. DeLuca, Status and results of ANL life evaluation of valve-regulated lead/acid load-levelling batteries; (c) G. R. Grefe, Evaluation of two stacked valve-regulated batteries for utility cycling application.

6 *Proc. 4th Int. ILZRO Lead/Acid Battery Seminar, San Francisco, CA, Apr. 25–27, 1990,* ILZRO. (a) G. D. Rodriguez, Operations and test program status of the Chino 10 MW battery energy storage project; (b) W. H. DeLuca, Status of Argonne life evaluation of valve-regulated lead/acid batteries; (c) B. Zickefoose, Crescent peak-shaving battery system — final report; (d) B. Reichman, Deep-discharge cycling of gelled lead/acid battery strings.

7 *Batteries Int., 4* (July) (1990). (a) K. Peters, Battery business . . when and where, pp. 14–14; (b) J. L. Haering, A Spanish load-levelling project, p. 16; (c) B. Voigt, T. Mierke and H.-J. Heinrichs, A battery for the Berlin subway, p. 18; (d) F. Steffans, A Swiss view of the opportunities, pp. 20–25; (e) W. C. Spindler, An up-date on U.S. storage schemes, pp. 28–29; (f) K. Krämer, BEWAG plan Berlin's new system, pp. 32–33; (g) G. H. Brilmyer, Proving tests in a brass foundry, pp. 36–37.

8 G. M. Cook, Overview of battery power regulation and storage, to be published.

9 D. A. J. Rand and W. G. A. Baldsing, Development of lead/acid batteries for domestic remote-area power supplies, *J. Power Sources, 23* (1988) 233–244.

10 D. W. H. Lambert, *Batteries Int., 5* (Oct.) (1990) 24–27.

11 C. Bohle and R. Kiessling, High performance maintenance-free lead/acid batteries, *Battery Man, 31* (Oct.) (1989) 18–22.

12 J. W. Hurwitch and C. A. Carpenter, Battery requirements and applications for low-maintenance lead/acid battery storage, in A. R. Landgrebe, U.S. DOE and G. M. Cook, EPRI (eds.), *Rep. Meet. Redwood City, U.S. DOE and EPRI, CA, Feb. 7–8, 1990.*