Batteries for Large-Scale Stationary Electrical Energy Storage

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Large-scale stationary battery energy storage has been under development for several decades with the successful use of pumped hydroelectric storage as a model. Several large battery demonstration projects have been built and tested under a variety of electric utility grid applications. In addition, renewable energy sources such as wind and photovoltaics may require energy storage systems. While these applications are new and expanding, the shift toward an expanded role for battery energy storage in the de-regulated electricity market became evident by the late 1980s and early 1990s. Studies by Sandia National Laboratories identified opportunities for battery energy storage in the generation as well as on the transmission and distribution segments of the electric grid. Reports[1,2] from these studies describe battery storage application requirements and provide a preliminary estimate of potential costs and benefits of these applications for the U.S. electric grid. Applications fall into two broad categories: energy applications and power applications. Energy applications involve storage system discharge over periods of hours (typically one discharge cycle per day) with correspondingly long charging periods. Power applications involve comparatively short periods of discharge (seconds to minutes), short recharging periods, and often require many cycles per day.

Detailed performance criteria for applications such as peak shaving and load leveling (energy applications) as well as frequency and voltage regulation, power quality, renewable generation smoothing and ramp rate control (power applications) are described elsewhere.[2] Generally, the most important requirements have been the need for low cost, flexible designs, proven battery technologies, and reliable performance.

While many battery technologies have been proposed and developed for electrical energy storage applications, only a handful have actually been used in fielded systems. Technologies that are used in fielded systems include lead-acid, nickel/cadmium, sodium/sulfur, and vanadium-redox flow batteries. Cost effective energy storage systems have been identified[3] for utility, end-user, and renewable applications. Other battery technologies, such as the many lithium-ion batteries, are less mature and not yet well-developed for these applications.[4]

There are many examples of large-scale battery systems in the field. Table I provides a short list of examples of installed large battery systems.

Secondary batteries, such as lead-acid, nickel-cadmium, and lithium-ion batteries can be deployed for energy storage, but require some re-engineering for grid applications. Two novel classes of battery systems that are relevant to new installations of large energy storage systems are sodium/sulfur (Na/S) and flowing electrolyte batteries. Each of these batteries is briefly described below, and information related to large battery applications is highlighted.

Secondary Batteries

Grid stabilization, or grid support, energy storage systems currently consist of large installations of lead-acid batteries as the standard technology. The primary function of grid support is to provide “spinning reserve” in the event of power plant or transmission line equipment failure, that is, excess capacity to provide power as other power plants are brought online. These systems can take energy from the grid when either the frequency or voltage is too high and return that energy to the grid when the frequency or voltage begins to sag. The current implementation can provide a few minutes of energy, but overall grid management, including shifting peak loads, and supporting renewables, will require longer durations of storage and therefore re-engineering of conventional storage systems to handle greater energy/power ratios. Some improvements can be made by re-engineering of existing secondary battery technologies; longer discharge durations will generally require new chemistries and system designs.

The lead-acid battery chemistry can be modified for grid storage applications beyond stabilization applications by modification of the electrode structures. Lead-carbon electrodes are designed to combine high energy density of a well-designed battery with the high specific power obtained via charging and discharging of the electrochemical double-layer. Lead-carbon electrode research has been focused on the extension of cycle life durability and specific power. Carbon is added to the negative electrodes; while the carbon does not change the nature of the charge-transfer reactions, it increases specific power and reduces the incidence of sulfation during charging cycles, which is one of the principal failure modes of traditional lead-acid batteries.[5] In these applications, we would like to have relatively deep discharges with good cycle life. Recent studies at Sandia have shown that new carbon-enhanced negative electrodes in valve-regulated lead-acid (VRLA) batteries have improved cycle life up to a factor of 10 at significant rates (up to 4C).[6]

Lithium-ion batteries, which have achieved significant penetration into the portable/consumer electronics markets and are making the transition into hybrid and electric vehicle applications, have opportunities in grid storage as well. If the industry’s growth in the vehicles and consumer electronics markets can yield improvements and manufacturing economies of scale, they will likely find their way into grid storage applications too. Developers are seeking to lower maintenance and operating costs, deliver high efficiency, and ensure that large banks of batteries can be controlled. As an example, in November 2009, AES Energy Storage and A123 Systems announced the commercial operation of a 12 MW frequency regulation and spinning reserve project at a substation in the Atacama Desert, Chile. Continued cost reduction, lifetime and state-of-charge improvements, will be critical for this battery chemistry to expand into these grid applications.

Sodium-Beta High Temperature Batteries

Rechargeable high-temperature battery technologies that utilize metallic sodium offer attractive solutions for many large-scale, electric utility energy storage applications. Candidate uses include load-leveling, power quality and peak shaving, as well as renewable energy management and integration. A number of sodium-based battery options have been proposed over the years, but the variants that have been developed the furthest are referred to as sodium-beta batteries. This designation is used because of two common and important features: liquid sodium is the active material in the negative electrode, and the beta-alumina ceramic separator functions as the electrolyte. Sodium/sulfur technology was introduced in the mid-1970s.[7] The advancement of this technology has been pursued in a variety of designs since that time.

A sodium-sulfur (Na/S) battery is a type of molten metal battery constructed from sodium (Na) and

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sulfur (S). This type of battery has a high energy density, high efficiency of charge/discharge (89-92%), long cycle life, and is fabricated from inexpensive materials.[8] However, because of the operating temperatures of 300°C to 350°C and the highly corrosive nature of the sodium polysulfide discharge products, such cells are primarily suitable for large-scale, non-mobile applications such as grid energy storage. Sodium β''-Alumina (beta double-prime alumina) is a fast ion conductor material and is used as a separator in several types of molten salt electrochemical cells. The primary disadvantage is the requirement for thermal management, which is necessary to maintain the ceramic separator and cell seal integrity.

In the mid-1980s, the development of the sodium/metal-chloride system was launched.[9] This technology offered potentially easier solutions to some of the development issues that sodium/sulfur was experiencing at the time. Sodium/metal chloride cells, referred to as ZEBRA cells (ZEolite Battery Research Africa), also operate at relatively high temperatures, use a negative electrode composed of liquid sodium, and use a ceramic electrolyte to separate this electrode from the positive electrode. In these respects, they are similar to sodium/sulfur cells. However, sodium/metal chloride cells include a secondary electrolyte of molten sodium tetrachloroaluminate ($NaAlCl_4$) in the positive electrode section, and an insoluble transition metal chloride ($FeCl_2$ or $NiCl_2$) or a mix of such chlorides, as the positive electrode. The advantages are that the cells have a higher voltage, wider operating temperature range, are less corrosive and have safer reaction products.

From the time of their inventions through the mid-1990s, these two technologies were among the leading candidates believed to be capable of satisfying the needs of a number of emerging battery energy-storage

Table I. Examples of installed large scale battery energy storage systems.

Name	Application	Operational Dates	Power	Energy	Battery Type	Cell Size & Configuration	Battery Manufacturer
Crescent Electric Membership Cooperative (now Energy United) BESS, Statesville, NC, USA	Peak Shaving	1987-May, 2002	500 kW	500 kWh	Lead-acid, flooded cell	2,080 Ah @ C/5; 324 cells	GNB Industrial Battery, now Exide Battery
Berliner Kraft- und Licht (BEWAG) Battery System, Berlin, Germany	Frequency Regulation and Spinning Reserve	1987-1995	8.5 MW in 60 min of frequency regulation; 17 MW for 20 min. of spinning reserve	14 MWh	Lead-acid, flooded cell	7,080 cells in 12 parallel strings of 590 cells each; Cell size: 1,000 Ah	Hagen OCSM cells
Southern California Edison Chino Battery Storage Project, CA, USA	Several "demo" modes including load-leveling, transmission line stability, local VAR control, black start.	1988-1997	Energy: 14 MW	40 MWh	Lead-acid, flooded cells	8,256 cells in 8 parallel strings of 1032 cells each; Cell size: 2,600 Ah	Exide Batteries GL-35 cells
Puerto Rico Electric Power Authority (PREPA) Battery System, Puerto Rico	Frequency control and spinning reserve	11/1994-12/1999	20 MW	14 MWh	Lead-acid, flooded cell	6,000 cells in 6 parallel strings of 1000 cells each; Cell size: 1,600 Ah	C&D Battery
PQ2000 installation at the Brockway Standard Lithography Plant in Homerville, Georgia, USA	Power Quality, Uninterruptable Power Supply	1996-2001	2 MW	55 kWh	Lead-acid	2000 Low-Maintenance, Truck-Starting Batteries, 48 per 250 kW module, 8 modules per 2 MW PQ2000 system	AC Battery, acquired by Omnion Power Engineering in 1997, in turn acquired by S&C Electric in 1999
Metlakatla Power and Light (MP&L), Alaska, Battery System, Alaska, USA	Voltage regulation and displacing diesel generation	1997-present	1 MW	1.4 MWh	Valve regulated lead-acid Absolyte IIP	1,134 cells/378 ea., 100A75 modules in 1 string	GNB Industrial Battery, now Exide Technologies, and General Electric
Golden Valley Electric Association (GVEA) Fairbanks, Alaska, USA	VAR Support, spinning reserve, power system stabilization	9/19/2003-present	27 MW	14.6 MWh	Nickel/cadmium type SBH920 cells	4 strings of 3,440 cells each, for a total of 13,760 cells	ABB and Saft
AEP Sodium Sulfur Distributed Energy Storage System at Chemical Station, N. Charleston, WV, USA	Substation upgrade deferral	2006-present	1.0 MW	7.2 MWh	Sodium/Sulfur	50 kW NAS battery modules, 20 ea	NGK Insulators LTD (battery)/ S & C Electric Co. (balance of system)
Long Island, New York Bus Terminal Energy Storage System, NY, USA	Load Shifting	2008-present	1.2 MW	6.5 MWh	Sodium/Sulfur	20 ea. 50 kW (60kW peak) NAS battery modules	NGK Insulators LTD (battery)/ABB Inc. (integration and balance of system)
Vanadium-Redox Battery at the Sumitomo Densetsu Office, Osaka, Japan	Peak Shaving	2000-present	3 MW	800 kWh	Vanadium-Redox Flow Battery	50 kW Sumitomo battery modules	Sumitomo Electric Industries (SEI) of Osaka, Japan
Pacificorp Castle Valley, Utah Vanadium-Redox Battery (VRB) System, Utah, USA	Distribution line upgrade deferral, voltage support	March 2004-present	250 kW	2 MWh	Vanadium-Redox Flow Battery	50 kW Sumitomo battery modules, 250 kW for 8 hours	VRB Power Systems (purchased by Prudent Energy Co., Beijing, China in 2009)

applications. The one application that generated the most interest centered on powering electric vehicles (EVs). However, the EV market was very slow to develop, and with the handicap of elevated temperature operation, support for most of the developers of the sodium-beta battery technologies was terminated.

The dominant organization that is presently developing and commercializing the sodium/sulfur technology is a Japanese collaboration between NGK Insulator, Ltd., and Tokyo Electric Power Company (TEPCO), that started in 1984.[10] Their goal is to develop cells with sufficient energy capacity for use in utility-based load-leveling and peak-shaving applications that require up to an 8-hr discharge period. The critical technology for such cells involved the manufacture of large diameter beta-alumina tubes of very high quality and precise dimensions.

Battery-level components include mechanical supports for the cells, a thermal management system (incorporating the thermal enclosure) to ensure that each cell is maintained at a relatively high temperature (*e.g.*, for Na/S from 300°C to 350°C), electrical interconnects (cell-cell, cell-module, module-battery), possibly cell-failure devices, and safety-related hardware (such as thermal fuses). Batteries are assembled by connecting cells into series and series-parallel arrays to produce the required battery voltage, energy, and power. Electrical heaters are installed within the enclosures to initially warm the cells and then to offset heat loss during periods while the battery is at temperature but idle. Normally, extra heat is not required during regular discharging and charging due to ohmic heating and chemical reaction effects.

As discussed above, stationary applications represent a very promising use for the sodium/sulfur technology primarily because of its small relative footprint (high energy density), excellent electrical efficiency if routinely used, integral thermal management, lack of required maintenance, and cycling flexibility. The developers have adopted a similar design approach for their battery systems that involves the use of self-contained modules, each with 10 to 50 kW of power and 50 to 400 kWh of energy. That is, independent battery-level modules are manufactured that consist of various series-parallel configurations of cells within a thermal enclosure. The battery itself is then constructed by connecting these modules in a series-parallel arrangement (often in a common structure) to give the desired voltage, energy, and power. The resultant battery is combined with a power-conversion system and controller to form an integrated facility that can be connected to an electrical system (either utility or customer side).[11]

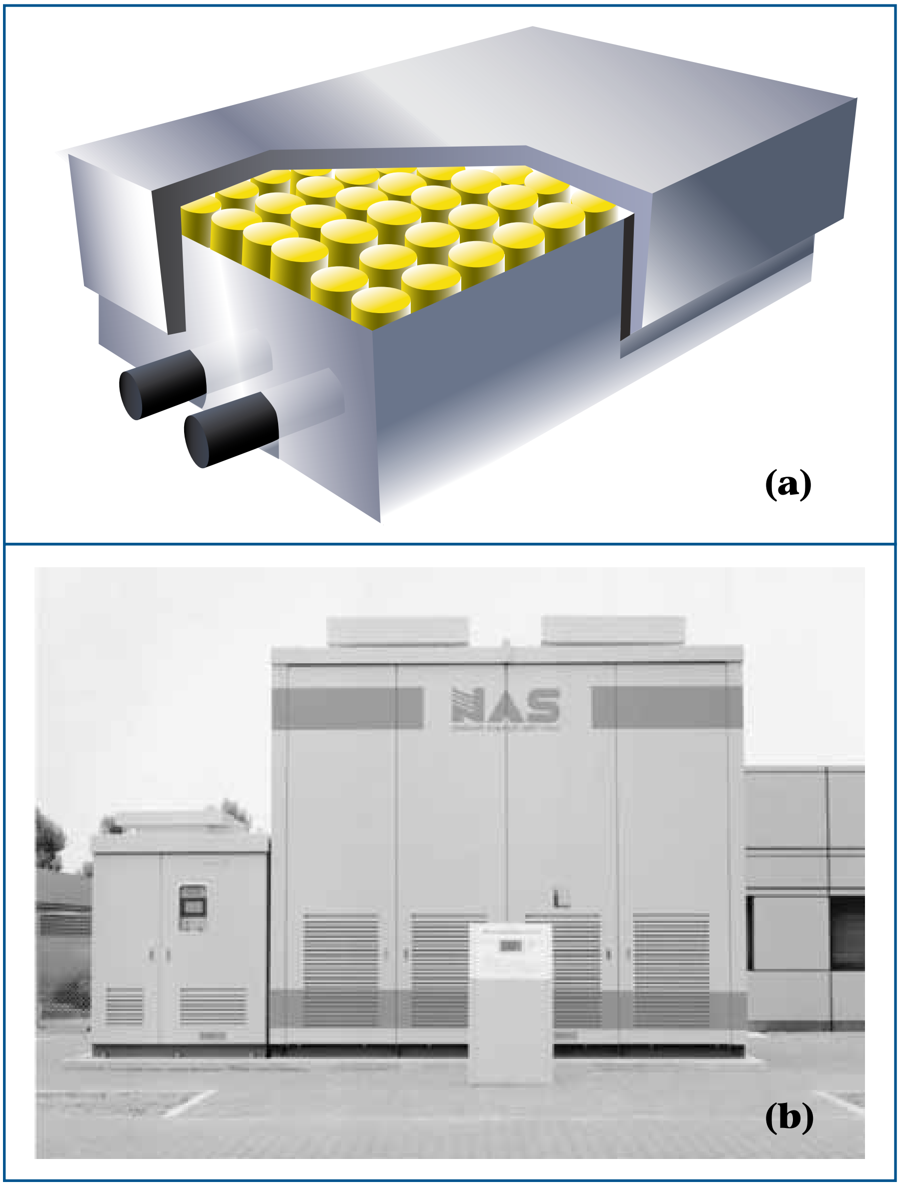

Fig. 1. *NGK stationary-energy-storage batteries: (a) the 50 kW modular battery component; and (b) an integrated 500 kW/ 4 MWh demonstration battery system that uses 10 of these modular batteries, operating since June 1998, and still in use as of January 2010.*

Yuasa built and operated the first large sodium/sulfur battery, an integrated 1-MW 8-MWh system, in the early 1990s that contained 26,880 cells.[12] This effort was part of the Japanese national research program called the Moonlight Project. Battery performance was demonstrated in a utility load-leveling application. Their program reached the proof-of-concept stage, but was terminated.[13]

The NGK modular concept and its implementation, which has been successfully fielded in several applications, including those described in Table I, are pictorially shown in Fig. 1, which shows one of the NGK modules along with an integrated system that contains these 50-kW modules.

Table II describes fielded sodium/sulfur systems with an accumulated installed capacity of 365 MWh that have been deployed world-wide using NGK technology.

Flowing Electrolyte Batteries

A flow battery is a form of rechargeable battery in which electrolyte containing one or more dissolved electroactive species flows through an electrochemical cell that converts chemical energy directly to electricity. (*Ed. Note*: For a more detailed discussion of redox flow battery configurations and chemistries, see the article on "Flow Batteries" in this issue of *Interface*). Additional electrolyte is stored externally, generally in tanks, and is usually pumped through the cell (or cells) of the reactor, although gravity feed systems are also known. Flow batteries can be rapidly "recharged" by replacing the electrolyte liquid (in a similar way to refilling fuel tanks for internal combustion engines) while simultaneously recovering the spent material that would be "recharged" in a separate step.

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Table II. Na/S battery projects as of december 2009. (Courtesy of NGK.)

Name of Developer	Country	Location	KW	Start of Operation/Status
TEPCO (Tokyo Electric Power Company)	Japan	Many locations around Tokyo	200,000 (approx.)	As of the end of 2008
HEPCO (Hokkaidou Electric Power Company)	Japan	Wakkanai City, Hokkaido	1,500	Feb. 2008
Other Japanese Electric Companies	Japan	Many locations other than Tokyo area	60,000 (approx.)	As of the end of 2008
JWD (Japan Wind Development Co., Ltd.)	Japan	Rokkasho Village, Aomori	34,000	Aug. 2008
AEP (American Electric Power)	USA	Charleston WV, Bluffton OH, Milton WV, Churubusco IN, Presidio, TX	11,000	4 sites except for Presidio: July 2006~Jan. 2009; Presidio: Shipped in Nov. 2009
NYPA (New York Power Authority)	USA	Long Island, NY	1,000	April 2008
PG&E (Pacific Gas and Electric Company)	USA	Not decided	6,000	Shipped in 2008
Xcel	USA	Luveme, MN	1,000	Nov. 2008
Younicos	Germany	Berlin	1,000	July 2009
Enercon	Germany	Emden, Lower Saxony	800	July 2009
EDF	France	Reunion Island	1,000	Dec. 2009
ADWEA (Abu Dhabi Water & Electricity Authority)	UAE	Abu Dhabi	48,000	Partially operated
Total			**365,300**	

The major advantage of this battery is that power and energy are not coupled in the same way as other electrochemical systems, which gives considerable design latitude for stationary applications. Additional advantages are good specific energy and recharge efficiency, low environmental impact, and low cost. The disadvantages of this battery technology are system complexity and high initial self-discharge rate.

Work on developing flow batteries started with the invention of the zinc/chlorine hydrate battery in 1968.[14] This system was the subject of development for EV and electric utility storage applications from the early 1970s to the late 1980s in the United States, and from 1980 to 1992 in Japan. Most work on zinc/chlorine batteries stopped at that time, but recently has been restarted. Currently there are two main types of flowing electrolyte batteries that are under development: zinc/bromine and vanadium-redox. A comparison of flowing electrolyte batteries for utility applications has been published.[15]

The vanadium-redox battery (VRB) technology is continuing to be developed and installed (see Table I). Efforts are focused on improved efficiency by reducing self-discharge losses and on lower cost electrode structures. Self-discharge is being addressed by only pumping electrolyte through the electrochemical stacks when necessary due to the magnitude of the load. These efforts are continuing.

The PacifiCorp VRB in Castle Valley, UT, is a 250 kW, 2 MWh system that was installed to defer for at least four years the installation of a major new 69 kV transmission line and substation in an environmentally sensitive area. The system cost $1.3 M to build and install, while the new transmission facilities are expected to cost over $5 M. The system was installed in late 2003 and became operational in March, 2004[16] (see Fig. 2). This was the first VRB system installed in North America. Prudent Energy Inc., based in Beijing, China, purchased VRB Power Systems in early 2009 and continues development of these systems.

Conclusion

Electrical energy storage using batteries is continuing to evolve technologically, and is increasingly being accepted as a viable and potentially revolutionary resource which could fundamentally change the way electricity is generated and used. More and more, battery storage is being considered for integration with renewable systems to increase the availability and value of those resources. The use of a single storage facility in multiple applications for utility grid systems is also expanding and becoming recognized for its value. As the cost of energy storage systems decreases and their reliability increases with improved technologies, these trends are likely to accelerate and make battery storage an essential part of the electricity delivery system.

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Fig. 2. *Exterior and interior views of the 2MWh VRB system at Castle Valley, UT.*

Since 1989 Nancy has been a project lead on DOE Energy Storage Programs. The projects have covered a wide range of advanced energy storage technologies including zinc bromine, zinc air, nickel metal hydride, lithium ion, advanced lead acid batteries, composite flywheels, and ultra capacitors. She has managed millions of dollars for the Department of Energy programs over the past 20 years. Most recently she managed the DOE program that delivered the first advanced energy storage technology used as part of the electricity infrastructure of a public utility. Based on the success of that program, she is managing a follow-on program that will add three more systems to the utility's infrastructure. Dr. Clark is well known in the energy storage field as the conference organizer for two international electrical energy storage applications and technologies conferences.

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