ASSESSMENT OF ALTERNATIVES TO LEAD-ACID BATTERIES FOR SUBSTATIONS

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ABSTRACT

More than 100,000 substation battery installations in the US represent a strategic investment for utilities. These batteries are typically drawn upon to provide power to switching components and to power the substation control equipment in times of AC power loss. They require regular maintenance and are sometimes seen as unpredictable in performance and life expectancy. New technology is one answer to challenges in design, operation, and maintenance of substation backup power systems. Examples that may provide cost-effective alternatives to the traditional lead-acid battery are advanced batteries, ultracapacitors, and fuel cells. This paper describes ongoing research by EPRI to survey and evaluate current practices in specifying, sizing, and maintaining lead-acid batteries, and to assess the potential for replacing these with new technologies. Survey findings of current utility practices show areas where new technologies may be beneficial. The paper will also report ongoing testing of several technologies in a substation role, including lithium batteries and fuel cells.

BACKGROUND

EPRI and participating electric power delivery companies are conducting ongoing research to improve the design, performance, and maintenance of substation emergency power systems. EPRI has reported results of surveys [1], and a study on utility practices for substation batteries [2], and measurements of loads at actual substations compared to loads projected during design [3]. This paper describes on-going research into replacement or augmentation of lead-acid batteries with new technologies when beneficial from a performance or cost perspective.

EPRI results described a survey of utility practices and attitudes toward sizing, installation, and maintenance of substation backup energy systems. This survey found that the dominant technology used for these systems is the vented lead-acid battery. Valve-regulated lead-acid (VRLA) batteries are still used in a significant number of installations, but are generally being replaced with vented lead-acid systems due to disappointing life performance. Nickel-cadmium batteries are used in 5% of locations described in the survey.

Most of the surveyed users seem satisfied with vented lead-acid batteries, which generally meet the 15-20 year life requirements and usually meet the discharge requirements during the occasional outage. While there were some complaints about the level of resources required to maintain the batteries, these comments seem more related to preventive maintenance and monitoring than to the technology itself. Maintenance costs are rarely tracked, making it difficult to quantify time and resources required for battery maintenance compared to other maintenance performed on substation hardware.

Utilities are cautious about replacing the existing technology without many successful field trials. This reflects the poor experience with other replacement technologies in the past, particularly valve-regulated lead-acid (VRLA) batteries in the 1980s and 1990s. VRLA batteries were sold as being able to meet the required 15-20 year life while requiring no maintenance, unlike conventional vented lead-acid batteries. In reality, the batteries rarely lasted more than 5 years; in extreme conditions, the life could be as short as 2 years. Furthermore, while vented lead-acid batteries could be monitored through electrolyte level and specific gravity measurements, the state-of-health of VRLA batteries could be monitored reliably only by performing a full capacity test. This bad experience has made many users very skeptical about newer technologies replacing conventional lead-acid batteries in this application.

Despite the apparent success of vented lead-acid systems and bad experiences with alternatives to date, the survey showed moderate interest among utilities in trying new technologies for substation backup power systems. Naturally, such interest is predicated on extensive testing and characterization of the alternative technology, as well as some significant advantage over the existing technology, in terms of maintenance costs, reliability, or better tolerance of extreme conditions.

The further research report in [3] involved the monitoring of substation equipment to evaluate the changing nature of substation dc loads. Substations built in different periods were included in the study, so that equipment changes could be studied. It was found that where compressed air and spring-actuated systems were used for switches and breakers in older substations, they have been replaced by dc motor-driven equipment in newer substations, for the reason that the latter systems are much easier to install and maintain. The result is that the loads on modern substation batteries are somewhat larger than on systems built 50 years ago.

It is important to look at the nature of these load increases. The dc loads in a substation is divided into three types by IEEE Standard 485, the sizing document for substation batteries:

- *Continuous loads:* Those loads energized throughout the battery duty cycle, such as relays, continuously operating motors, inverters, emergency lighting, energized coils, and control and communications systems.

- *Non-continuous loads:* Loads which are energized only during a portion of the battery duty cycle. These loads may come on at any time within the duty cycle, and may be on for a set length of time and then be removed automatically or by operator action, or may continue to the end of the duty cycle. These loads include pump motors, ventilation system motors, fire protection system actuators, motor driven valves, and lighting.

- *Momentary Loads:* These are loads which occur one or more times during the battery duty cycle, but are of short duration not exceeding one minute at any occurrence. Although most momentary loads last for significantly less than a minute, or even a second, it is common practice to assume that the momentary load lasts one minute because the initial voltage drop often determines the battery's one-minute rating. Momentary operations include switchgear operation, motor-driven valves, isolating switches, field flashing of generators, motor starting currents, and inrush currents.

The majority of load growth observed in substations has occurred in momentary loads. This means that batteries often have to be significantly oversized from an ampere-hour standpoint to ensure that the battery can continue to maintain a voltage level about the requirements of the system, which are often determined by the low voltage ratings of electronics controls. Lead-acid batteries have some difficulty with this requirement because of effects such as coup de fouet. This, together with design conservatism involved in sizing, has lead to gross oversizing in many lead-acid substation systems. There is some incentive to find alternative technologies which do not have problems meeting high current requirements for brief periods of time.

Based on these results, the next step in our research is to identify technologies which fit the requirements for substation batteries and evaluate them from technical and economic perspectives to determine which have the most potential in this application. In particular, we are looking for technologies which result in a system that is easier to maintain and evaluate in terms of reliability.

ALTERNATIVE TECHNOLOGIES FOR SUBSTATION BACKUP ENERGY SYSTEMS

Several different technologies are under consideration as replacements for conventional vented lead-acid batteries in this application. As mentioned above, a significant number of sites use valve-regulated lead-acid (VRLA) batteries or vented nickel-cadmium batteries. Other battery technologies under consideration include nickel-metal hydride, lithium-ion, and lithium metal polymer. All of these battery systems are expected to meet substation requirements without other supplementary energy sources. Non-battery energy sources, such as ultracapacitors, flywheels, and fuel cells, also show some potential in this area but need to be supplemented.

In cases where the characteristics of a single technology preclude a practical solution, than pairing with a complimentary technology to provide a hybrid system solution may be considered. For example the flywheel or capacitor will require additional energy sources to pair with, such as fuel cell or battery. Fuel cells do not typically have the instantaneous response time or the inrush current capabilities required for substation backup power. A zinc-air battery would also require a supplemental power source to pair with, such as a capacitor or lead-acid battery. Hybrid systems offer the advantage of separating power and energy such that the size can be matched to the load requirements.

Hybrid systems may make sense even with existing lead-acid batteries. A substation battery is typically sized according to a power profile, to ensure that it can support the current required by all loads that are likely to occur at the same time, even if those loads do not last for a very long time. This often means that the battery is significantly oversized from a capacity standpoint. An ultracapacitor, on the other hand, can more easily support high currents for a short period of time. For this reason, it is possible to build a battery-ultracapacitor hybrid significantly smaller than a lead-acid battery sized for the same loads.

Table 1 describes several technologies that have been considered for substation backup power applications, along with some of their advantages and disadvantages. Not all of these technologies have been tested in this application. Indeed, for many of these technologies, there are few products designed for such an application. In such cases, the general capabilities of the technology are considered in the context of a long float voltage application.

Table 1: Potential Technologies for Substation Backup Power Systems

Independent Operating Electric Storage Technology

Technology	***Advantages***	***Disadvantages***	***Major Manufacturers***
Vented Lead-acid (Default)	Mature and well-known Low initial cost Long life	Coup de fouet Relatively intolerant of temperature extremes	Enersys GNB (Exide)
Valve-Regulated Lead-Acid	Low maintenance Low initial cost	Coup de fouet Intolerant of temperature extremes, Short life	C&D Technologies Hawker Energy (Enersys)
Vented Nickel-Cadmium	Mature and well-known Long life Relatively tolerant to temperature extremes	Low cell voltage Float effect makes capacity testing difficult	Saft Alcad
Lithium ion batteries	High energy density Long life	Relatively unknown and untested High initial cost (at present) Requires balancing and charge control electronics	Valence Johnson Controls (formerly Varta)
Lithium metal polymer batteries	High energy density Tolerant to temperature extremes	Relatively unknown and untested High initial cost (at present) Requires balancing and charge control electronics	Avestor
Nickel-Metal Hydride	High energy density	Untested in this application Low cell voltage Intolerant of temperature extremes Float effect makes capacity testing difficult	Johnson Controls (formerly Varta) Electro Energy
Sodium sulfur batteries	High energy density	Relatively unknown and untested High initial cost (at present)	NGK Insulator

Hybrid Pairs	Zinc-bromine batteries, (needs power partner)	High energy density Flat voltage profile	Relatively unknown and untested Mechanical parts require maintenance May require occasional stripping cycles	ZBB Energy
Hybrid Pairs	Regenerative zinc-air, (needs power partner)	High energy density	Relatively unknown and untested Voltage drop at start of discharge Limited shelf and cycle life	Metallic Power
Hybrid Paris	Ultracapacitors, With energy partner	High current density	Relatively unknown and untested High initial cost (at present) Low energy density, probably not viable alone	Maxwell NESS Capacitor ESMA
Hybrid Paris	Flywheels	High current density Long life	Relatively unknown and untested High initial cost (at present) Low energy density, probably not viable alone	Active Power Beacon Power
Backup Power Technologies	Diesel/NG genset with VLA batteries	Mature technology Indefinite run time	Additional maintenance and fueling required	-
Backup Power Technologies	Diesel/NG genset with ultracapacitors	Indefinite run time	Ultracaps are relatively untested Additional maintenance and fueling required	-
Backup Power Technologies	Diesel/NG genset with flywheel	Indefinite run time	Flywheels are relatively untested Additional maintenance and fueling required	-
Backup Power Technologies	Fuel cell with VLA batteries	Indefinite run time	Fuel cells are relatively untested Additional fueling required	-
Backup Power Technologies	Fuel cell with ultracapacitors	Indefinite run time	Fuel cells and ultracaps are relatively untested Additional fueling required	-
Backup Power Technologies	Fuel cell with flywheel	Indefinite run time	Fuel cells and flywheels are relatively untested Additional fueling required	-
Backup Power Technologies	VLA Battery with ultracapacitors	Battery can be sized for Ah instead of voltage level	Ultracaps are relatively untested High cost of ultracapacitors	-

As noted before, two technologies besides vented lead-acid batteries already have some market share in the substation battery market: VRLA batteries and vented nickel-cadmium batteries. The technical and market successes and failures related to these technologies tell us what will be expected from future technologies. In particular, the following observations can be made.

A successful technology will maximize reliability while minimizing maintenance requirements. In an application where reliability is the key criterion for performance, initial costs rarely play into the purchasing decision. Even maintenance costs are not much considered in the initial decision. Repeated, time-consuming maintenance procedures have a high nuisance factor, however, and most users would rather spend their scant resources on other problems.

The state-of-health of the battery should be capable of being measured without capacity testing. A significant problem with VRLA batteries is that the specific gravity of the electrolyte cannot be easily tested, necessitating the laborious and time-consuming procedure of regular capacity testing. This is particularly frustrating since the life of VRLA systems is very sensitive to the operating environment, and the systems can fail without warning. Ideally, a new technology used in substation backup power systems should be capable of a simple test which will show the present state-of-health of the battery, allowing maintenance personnel to decide on corrective procedures or replacement before an exigency arises.

Changes in battery performance as the battery ages should be graceful. Many systems tend to perform well for some time, and then fail suddenly. This is a difficult failure mode to handle, since it is difficult to tell whether a battery replacement must be performed immediately or can be deferred to the next maintenance cycle. Other batteries lose capacity gradually in a well-understood fashion. This is highly desirable since a simple calculation can show when a battery should be replaced.

Maintenance operations requiring significant times and supervision by personnel are very likely to be ignored. This includes capacity tests, reconditioning procedures, and other time-consuming maintenance activities. In general, many if not most users will choose not to perform such operations, and will choose not to use technologies that require such operations on a regular basis. This is borne out by the survey of utility users, which found that only 44% of respondents conduct regular capacity tests. Customers are unlikely to be satisfied with technology that requires such operations to meet the advertised performance.

As momentary loads at substations increase, technologies that can support high currents for brief durations will seem more attractive. Substation batteries are sized by two important factors: the duration that the battery must support the load (a Whr requirement), and the ability of the battery to support, without dropping below a specified voltage, the maximum current drawn by the equipment. For lead-acid batteries, the latter requirement is often determined at the very beginning of discharge, due to effects such as coup de fouet, rather than at the end of discharge. For this reason, lead-acid batteries are often significantly oversized from a Whr perspective, so that they can meet the current requirement during inrush.

It can be argued that the level of conservatism in the present design is grossly excessive, especially since margin is often piled on top of margin. It is unlikely that an inrush current measured in milliseconds drops the voltage sufficiently to take controls offline, let alone the motors themselves. Present design methodologies suggest adding inrush currents that may occur simultaneously, leading to an even greater current requirement. Finally, most engineers routinely add a further level of margin at the end of the calculation, leading to a battery that is often several times larger than it needs to be.

While design methodologies for lead-acid batteries should be re-examined in this light, there is also an opportunity for other technologies, which are not as restricted in delivering inrush currents and therefore do not need to be oversized for capacity. In particular, vented nickel-cadmium, lithium ion, and hybrids with ultracapacitors have some potential in this area.

Clearly, the ideal backup power technology for a substation application would meet all performance requirements while requiring no maintenance, would degrade over a period of 30 years in a predictable fashion that would allow determination of the exact state-of-health from a small number of easily measurable quantities. While the development of a technology with all of these characteristics is unlikely, it is possible that some of the technologies under consideration meet some of these requirements, or at least, come closer to meeting them than conventional lead-acid batteries. Any assessments in this direction must be backed up with field demonstrations that prove that the technology does, indeed, meet the stated performance.

EXISTING PROGRAMS

Some utilities have already begun programs to field test alternative technologies in substations. Most of these programs are in a very early stage and have yet to show extensive results. Initial reports have shown that these technologies can work in the application, but that existing lead-acid technologies are tough to beat from the standpoint of cost and value.

Lithium ion batteries have often been touted as a replacement for lead-acid batteries in a number of applications. Although somewhat expensive at the moment, the price is rapidly coming down as manufacturing methods mature. The relatively high energy densities of lithium ion batteries, and the high cell voltage, are significant advantages. Lithium ion cells are well-characterized and are relatively easy to test and assess. AEP and Sandia National Laboratories recently began a joint program to test lithium ion batteries in a substation application. The batteries used in the demonstration are built by Valence Technologies. Field testing began on the system in January 2004.

Hydrogen fuel cells have also elicited significant interest. The main advantage of such a system is that it will continue to provide power to the substation indefinitely, as long as hydrogen fuel is supplied to the system. Most fuel cells require small lead-acid batteries to provide immediate power during an outage, while the fuel cell starts up.

Several utilities have attempted to perform field tests with fuel cells in substations. Avista Corp. has installed fuel cells built by its subsidiary, Avista Labs, at a substation in the Northwestern U.S. Detroit Edison has explored the installation of Plug Power fuel cells at a substation in Michigan.

Finally, Alliant Energy initiated a program to assess a regenerative zinc-air energy storage system at a substation in Wisconsin. The vendor eventually withdrew from the program, citing the relatively small size of the substation battery market.

CONCLUSIONS

Although users have occasional complaints about vented lead-acid batteries, by and large they are satisfied with the operational performance and lifetime of these systems. The existing systems also have the advantages of relatively low cost and are extremely entrenched in the market. For this reason, any other technology will have a tough go in this market.

Nonetheless, there are areas in which other backup power technologies can compete. Users would be very glad to have a battery for which state-of-health can be easily determined from simple measurements; alternatively and just as desirable, would be a measurement or monitoring device that is able to make such a determination for existing technologies.

Similarly, as substation equipment continues to move towards more dc motors and actuators in place of electro-mechanical systems, there is an opportunity for new dc technologies able to meet inrush currents and momentary loads with better response than lead-acid batteries.

While these abilities would open the door for a new technology in this market, the product would have to go through many successful field trials before users would be open to replacing the existing technology. It is safe to say that any technologies under consideration are years away from any significant level of market acceptance.

REFERENCES

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