SOPHISTICATION VERSUS SIMPLICITY – SYSTEM DESIGN CONSIDERATIONS FOR LITHIUM-ION BATTERIES IN STANDBY POWER APPLICATIONS

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ABSTRACT

System architecture for traditional lead-acid and nickel-cadmium batteries has evolved in particular ways to meet specific application requirements. For example, valve-regulated lead-acid (VRLA) batteries for telecom outside plant (OSP) are deployed in multiple parallel strings, while vented batteries in utility substations are installed as single series strings. As users in these applications start to consider new technologies such as lithium-ion (Li-ion) there will be a natural tendency to maintain the same system architecture that has worked so well for them over the years. But is this the right decision?

Li-ion battery systems include built-in monitoring and communication functions that are required to ensure operational safety. These functions provide a level of sophistication that is not seen in traditional batteries, and, combined with the increased energy density of Li-ion, can seem to make a compelling argument in favor of this new technology. However, with increased sophistication come new failure modes and new complications in battery application, and these issues can have a serious impact if the system architecture and battery integration are not modified accordingly.

This paper addresses two applications – telecom OSP and utility substations – comparing existing battery solutions with Li-ion, and how the dc power system can be adapted and optimized to provide for successful application of Li-ion batteries. Recommendations are provided for the user to evaluate competing technologies, with particular reference to a soon-to-be published IEEE standards document.

LITHIUM-ION BACKGROUND

First shipped commercially around 1993, Li-ion technology has come to dominate successive applications for portable devices, first taking over the market for laptop computers, then mobile phones, then high-end digital cameras. Now this technology is penetrating the power tool market alongside the incumbent technologies. The earlier successes were driven by the superior energy density of Li-ion, and market gains in high-value applications such as laptops led to reduced costs, which in turn created new value propositions in the lower-end devices. More recently, the advent of high-power designs drove the adoption of Li-ion in the power-tool market.

The electrochemistry of choice for most portable applications is based on lithium cobalt oxide in the positives and graphite in the negatives. However, Li-ion technology covers a broad range of electrochemical systems, as discussed in a recent Battcon paper[1]. Longer lasting, more durable Li-ion technologies for electric vehicles have been under development for many years and are now starting to appear in production vehicles of various types, including hybrids, plug-in hybrids and full electric vehicles.

At the same time the battery industry itself is being transformed. The US Department of Energy recently awarded grants totaling $1.5 billion under the American Recovery and Reinvestment Act of 2009 (ARRA) for manufacturers of battery packs and cells, and suppliers of battery components, raw materials and recycling services, mostly related to Li-ion technologies.

So we have a situation in which consumers have become familiar with Li-ion technology, while the industry will soon experience a large increase in capacity in anticipation of the introduction of industrial type Li-ion batteries not only for automotive use but also for a broad range of stationary standby battery applications. The transition will be characterized by two major enhancements:

- Battery size: shifting from batteries of less than 1 kWh to systems of tens or hundreds of kWh, with the first megawatt-scale systems already on test today.

- Operating life: from 2 to 5 years of life for consumer goods (computers, mobile phones) to 5, 10 and up to 20 years of life for industrial capital equipment such as vehicles or power generation assets.

WHY LITHIUM-ION?

Most users are attracted to Li-ion batteries because of their small size and low weight compared to other technologies. However, there are many other characteristics of these batteries that can make them appear to be a good choice for a variety of standby applications. Some of these characteristics may be specific to particular electrochemistries; for example, lithium titanate negative active material can allow very high charge rates to be used. Other characteristics are more generic, such as the ability to tailor the performance type to the discharge duty (similar to UPS, general-purpose and telecom cell types in the lead-acid world).

The following is a partial list of Li-ion characteristics that could be beneficial in standby applications. Note that some benefits may not be available from all Li-ion technologies.

- High energy density and specific energy
- Long calendar life under sometimes stringent operating conditions
- Very good cycle life
- Very high round-trip (charge/discharge) energy efficiency
- No routine surveillance (self-diagnostic with alarm management capability)
- Reduced installation costs (high-voltage cells and modular construction)

SOPHISTICATION OR COMPLEXITY?

Aqueous electrochemistries like lead-acid and nickel-cadmium have side reactions involving water that provide a self-balancing characteristic, so that all cells in a series string behave similarly. Water in the electrolyte of those systems also provides a means for dissipating overcharge energy. In contrast, non-aqueous Li-ion systems are not self-regulating, so cell-level electronic subsystems must be used to provide a balancing function. Similarly, Li-ion systems use charge and discharge switches at string level to prevent overcharge and overdischarge.

Li-ion battery electronics provide important safety functions. A full discussion of Li-ion battery safety has been provided elsewhere[2] and is beyond the scope of this paper. The layered nature of these electronic systems is represented conceptually in Figure 1.

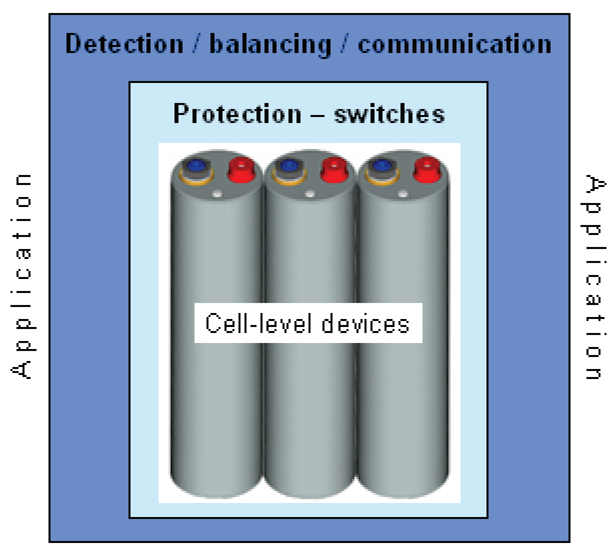

Figure 1. Layered structure of Li-ion battery electronics and protection

The outer layer shown in Figure 1 includes continuously active cell voltage and temperature detection, cell balancing and communication with the application (human-machine interfaces, control systems, battery chargers, etc.). The next layer includes the protective charge and discharge switches and is active only when necessary to prevent cell damage or a safety event. The innermost layer is represented by built-in cell-level safety devices, such as shut-down effect separators, current breakers and pressure-relief valves. These devices are activated only as a last resort, if the electronic systems have failed to prevent an abusive situation.

The addition of electronic subsystems and communications capability provides Li-ion batteries with an unprecedented level of sophistication. Battery management systems can take cell-level and battery-level measurements and apply algorithms to assess the battery's condition and to determine what level of charge or discharge can be undertaken. This information, along with warnings, alarms, and state-of-charge (SOC) and state-of-health (SOH) assessments, is sent through high-speed CANbus communication links to the host system. Thus these batteries have a self-diagnostic function that eliminates the need for routine maintenance.

On the other hand, the use of electronic subsystems represents a high level of complexity, with additional reliability and availability concerns, with regard to both internal system failures and external abuse situations (non-compliant operating conditions)

Battery inherent failure mechanisms

There is a large increase in the number of single points of failure in Li-ion batteries, e.g. if a single cell-voltage-sensing circuit should fail then the condition of that cell is unknown and the only prudent action is to shut the battery down and prevent its further use. It is therefore important that the system architecture be designed such that the failure of a single component does not render the entire system inoperable. In comparison, the most common single point of failure of a vented battery is a cell internal short circuit, which will reduce the battery performance to a certain extent, but does not prevent the battery from functioning.

Battery external abuse conditions

Likewise, a Li-ion battery needs protection against a number of external abuse situations, such as overtemperature, overvoltage or external short circuit. In case of such an event, the battery protection layer would normally prevent battery function either partially (e.g. prohibit charge but allow discharge) or totally, and either temporarily (until normal conditions are restored) or indefinitely. In comparison, aqueous batteries normally do not require such protective devices, as they can support abusive conditions to some extent without loss of the battery function. Abusive conditions may lead to temporary high temperature, water consumption or degradation of performance, but in the vast majority of situations do not inhibit the battery's fundamental function of providing backup energy and power.

SAMPLE APPLICATIONS

To assess how Li-ion batteries can effectively be applied in stationary standby-power operation, two sample applications will be examined: telecom outside plant (OSP) cabinets and utility substations. The following subsections discuss various aspects of these applications and of the operational needs of Li-ion batteries.

Traditional dc system architecture

OSP cabinets are frequently equipped with valve-regulated lead-acid (VRLA) batteries with the required capacity being split between multiple strings with no explicit redundancy. The typical discharge time is several hours and this makes the systems somewhat tolerant of the high-resistance or open-circuit failure mode that can occur with VRLA batteries—the run time would be reduced but this can generally be tolerated. More recently, nickel-cadmium (Ni-Cd) batteries have been introduced in this application with only minor changes in system setup. Charging in OSP cabinets is with modular rectifiers deployed with $N + 1$ redundancy. These rectifiers operate at a single charging voltage that is adjusted according to the battery temperature.

Vented lead-acid or Ni-Cd batteries are generally used in utility substations. These batteries have higher reliability than VRLA types and rarely fail open, so they are normally installed in single-string configurations. Many systems must supply relatively high switching currents (although this is less of a factor with solid-state switchgear) and this requirement makes it pointless to split the battery capacity between parallel strings without employing some level of redundancy. Charging in this application is normally accomplished with a single charger with two-level float/equalize operation and no temperature compensation of the charging voltage.

Application drivers for Li-ion

Li-ion batteries are sometimes considered for telecom OSP because cabinet loads are increasing while the battery space remains unchanged. There may also be a desire for longer life than that of VRLA batteries, and the no-maintenance/self-diagnostic characteristic of Li-ion batteries may be attractive.

Utilities are often seeking to deal with the retirement of battery specialists and maintenance technicians, so again the no maintenance/self-diagnostic characteristic can be attractive. A reduced footprint is generally not so important, although a Battcon paper from a few years ago discussed how avoiding the construction of a separate battery room in a Vattenfall substation in Sweden could make Li-ion batteries cost-effective[3].

Lithium-ion architecture

It is certainly possible to deploy Li-ion batteries as single strings, but this raises issues with system reliability, as discussed previously. To be sure, a problem can be immediately flagged through the communications link and it is quite possible that the system could be repaired before the next time the battery will be called on to operate, so availability could actually remain at a high level. This argument cannot of course be made if there is no communication between the battery and charger and/or to central operations, so a robust communications link is important. Even so, for critical applications it would be prudent to use multiple-string architectures for Li-ion.

The telecom OSP architecture is therefore quite appropriate for Li-ion batteries, while the critical role of substations dictates that the system be adapted to a multi-string architecture, with $N + 1$ redundancy being a requirement for systems with high switching currents. This may be a change that many conservative utility engineers would be reluctant to make.

Lithium-ion charging

Most Li-ion technologies are sensitive to the level of charge current that they can accept without damage. In addition, some technologies exhibit a sloping characteristic of voltage versus SOC. This characteristic is illustrated in Figure 2 for two positive materials: lithium cobalt oxide ($LiCoO_2$); and lithium nickel oxide doped with cobalt and aluminum (NCA). These technologies are discussed in detail in the previously referenced Battcon paper[1], but it can readily be seen that the applied charge voltage will dictate the SOC that will be reached in service.

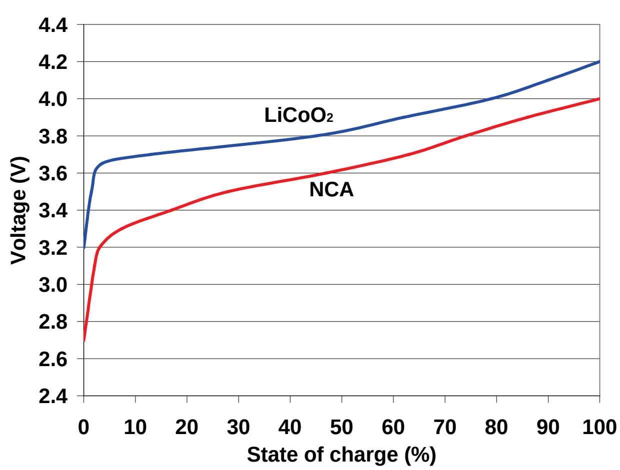

Figure 2. SOC vs. voltage characteristic for $LiCoO_2$ and NCA technologies

In telecom OSP cabinets with their $N + 1$ rectifier configurations there is a need to limit charge current, particularly since the rectifier shelf may be fully populated, even with low cabinet load. Many newer rectifiers have a 'battery current limit' feature that would provide the necessary functionality, but there is no guarantee that this feature would be enabled, or that it would be set to the correct level. Dynamic current limiting could be implemented in systems with CANbus control of the charge current, but this would not address the requirement in legacy OSP systems. The only universal solution in this case is to have a current-limiting feature built into the battery, either always on or enabled dynamically as needed.

Charging voltage is another issue that potential users should address. For the NCA technology shown in Figure 2, a 14-cell system should be charged at 4.0 V/cell, or 56.0 V at system level, to be maintained at 100% SOC. This voltage level is well within the tolerances of modern telecom equipment but it is above the 54.5 V value used for VRLA batteries. If a 14-cell NCA battery is charged at 54.5 V the individual cells will be at 3.9 V and will therefore be maintained at a little under 90% SOC.

Another aspect of charging in telecom applications is the widespread use of temperature compensation of the charging voltage. This feature must either be disabled or it must be optimized for Li-ion operation. If a battery is charged at 100% SOC at a certain temperature, then higher voltages must not be applied at lower temperatures. For higher temperatures it is possible to enhance the battery's operating life by reducing the voltage, but this would also lead to a reduction of SOC.

The charging situation in substations is quite different from telecom OSP. In most cases the available charge current is probably acceptable for Li-ion batteries, but charging must be at a single level only; a higher equalize voltage must not be applied. This means that the equalize setting in a substation charger would have to be disabled, or set to the same level as the float setting. In addition, the float voltage used for maintaining 100% SOC may be too high for permanent operation of connected loads.

For example, NCA cells normally operate from 4.0 V/cell down to 3.0 V/cell and standard modules may have 7 cells in series. In this case a 5-module battery (35 cells) would discharge down to the normal 105 V level that is typical for substation applications. However, this system would need to be charged permanently at 140 V to maintain 100% SOC—a level that could lead to indicator lamps and other connected equipment failing rather rapidly. One option might be to drop a cell from one or more of the modules—if this is indeed possible—but this would limit the discharge at the low end of the voltage window and would complicate module replacement strategies. Alternatively, the applied charge voltage could simply be reduced, knowing that this will also limit the SOC. In either case there are certain systems that would be very difficult to replicate with Li-ion. For example, the normal charge voltage of a 58-cell lead-acid battery is around 130 V and at this level a 35-cell NCA battery would be operating at just 65% SOC.

EVALUATING NEW TECHNOLOGIES

Looking beyond system architecture and operational considerations, simply trying to evaluate a new technology can be a tricky task. In many cases the developers of the new technology are using data derived from other applications where the operating conditions of standby power systems may not be valid. Worse, those developers may not fully understand the intended standby applications and may use terminology that is not understood by the potential user.

These difficulties are addressed by a new IEEE recommended practice soon to be published. The draft of IEEE 1679, "Recommended Practice for the Characterization and Evaluation of Emerging Energy Storage Technologies in Stationary Applications" has passed balloting and at the time of writing this paper was under consideration by the Review Committee of the IEEE Standards Board. IEEE 1679 aims to provide a level playing field in which developers of emerging battery and other energy storage devices will use a standardized approach in their submittals. The document also provides recommendations to potential users for evaluating these technologies for their applications.

It is hoped that IEEE 1679 will be published before the end of 2010 and that battery users will issue specifications requiring that the document's conventions be adopted by manufacturers. Work has also been started on the first in a series of subsidiary documents providing guidance on the application of IEEE 1679 for specific device classes. This first subsidiary document should ultimately become IEEE 1679.1, "Guide for the Characterization and Evaluation of Lithium Batteries in Stationary Applications."

CONCLUSIONS

Li-ion technology offers many advantages, and arguments in its favor can seem compelling. However, possible use of Li-ion should be properly evaluated. Existing system architectures and controls have evolved to suit the traditional battery technologies, and the benefits of Li-ion may not be realized unless the user is willing to adopt changes in these areas. For more conservative users the simplicity of existing technologies and architectures, particularly those with vented lead-acid and Ni-Cd batteries, may still be the best solution.

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