Considerations for Using Lithium-ion Batteries with UPS Modules

Rick Caudill
Senior Product Manager
Vertiv

Gregory W. Ratcliff
Director Life-Cycle Management
Vertiv

Introduction

Lithium ion (Li-ion) battery technology is making its inroads into high availability applications, including data centers. Failure of a data center's uninterruptable power supply (UPS) system can lead to substantial economic and customer/user satisfaction losses. Li-ion battery systems represent different risks, operational considerations, and costs when compared with lead-acid based systems.

This paper will describe the journey taken to prepare and qualify several UPS systems for reliable, highly available, and OEM approved operation utilizing Li-ion energy storage. Our goal is to equip a supporting business or end user that is considering any effort with Li-ion (ranging from a pilot project to initial production deployment) with the right questions to ask and help them understand the deliverables they should expect from their providers.

Complete Lifecycle Considerations

During our process of bringing this technology to market, practical operating considerations drove us to study the recurring and long-term implications of operating a Li-ion energy storage system. This included exploring three battery chemistries and two different management technologies. We (stationary battery businesses) have a large body of standards, best practices and field proven recommendations for both valve regulated lead-acid and vented lead-acid units. We asked ourselves what we should know about this new application, particularly after recognizing the growing demand for a less mature technology. We divide these considerations, and some as yet unanswered questions, into the areas related to safety, design, testing, specifying, installation, on-site acceptance, operation, services and managing failures and end of life. We have taken a time based (cradle-to-grave) approach to report our findings and observations. For this paper, we define manufacturers, integrators, battery management system developers and battery system providers collectively as the *manufacturer*.

Safety

Every energy source requires careful manufacturing, process, design and use. Organizations such as the Institute of Electrical and Electronics Engineers (IEEE) and Underwriter's Laboratories (UL) are actively producing standards to guide our market and end users. Improvements continue from manufacturers in key areas we consider paramount for stationary service near critical areas such as data centers and colocation facilities. These include chemistry, separators, management, and monitoring and detection.

UL1973 [1] (Batteries for Use In Light Electric Rail And Stationary Applications) is the correct standard for a stationary Li-ion battery system. UL1642 (Standard for Lithium Batteries), ANSI/UL 1998 [2] (Software in Programmable Components) and UL 991 [3] (Tests for Safety-Related Controls Employing Solid-State Devices) standards must be met to allow UL1973 listing. Safe operation of a Li-ion battery requires prevention of excessive battery temperature to avoid high temperature that will damage the battery's internal components.

Both passive and active battery management is required for battery protection. Passive management addresses high battery unit internal pressure. It is the active management functions that are more likely to be experienced during high rate, UPS service battery applications. Excessive charging or discharging current can cause internal damage, perhaps well before the internal temperature sensors can detect the internal battery temperature. For this reason there are many systems to monitor battery current. Excessive battery module temperature can result from battery cycling without sufficient time for the battery to cool down. UL requires automatic operation to prevent damage to the batteries. Battery management systems prevent damage to the battery system as a primary mandate; delivering power is secondary.

Transportation of Li-ion batteries is governed by the requirements of UN3840 (Class 9). Li-ion batteries cannot be shipped on a passenger plane and air or ocean transportation requires that the battery be up to 30% charged. Due to the difference in battery chemistries, storage and transportation temperatures vary significantly. Temperature control during shipment may be required.

Design and Testing

There are four key areas of consideration when integrating Li-ion into existing and new designs. Many of these new considerations are simply a new theme on the innovation and technology changes that have occurred over the years. Examples of a few key elements include string voltage for charge and recharge, string charge current, and temperature management. Modern medium and large UPS systems for example, are tolerant of the differences between valve-regulated lead acid, vented lead acid, nickel metal hydride and nickel cadmium battery technologies. Extending these changes to support Li-ion is a natural next step.

However, the operating characteristics of Li-ion are significantly different than the chemistries and architectures that preceded them. One characteristic, also discussed in the battery management systems (BMS) section below, is how the supporting electronics for stationary Li-ion execute a “disconnect” for their own protection. The battery voltage decrease at the end of discharge event is sudden and rapid, therefore designs supporting Li-ion must react and shutdown the UPS in an appropriate, protective manner. Some older designs may confuse a normal rapid drop in DC link voltage as a failure and misreport the change in voltage over time (dV/dT) as a breaker or fuse opening the circuit.

Another area of consideration for design includes recharge management. Li-ion string voltages naturally decrease during a discharge event. Unlike lead acid, a Li-ion battery in discharge remains at a lowered voltage after discharge. This results in several design and testing considerations. First, the rectifier voltage may be significantly higher than the battery string voltage at the beginning of the recharge cycle. This large difference in voltage could overload the recharge circuits if they are not protected or trigger a battery overcurrent disconnect event.

Li-ion battery systems manage temperature as a part of the safety strategy. During testing and integration, we measured that the internal temperature of the Li-ion battery system rises significantly during discharge events. Rapid recharge may increase the temperature or at minimum, delay the return to normal temperature. Li-ion battery manufacturers recommend a maximum recharge current that we determined will allow a return to nominal temperature within 24 hours.

The UPS manufacturers should provide a specific statement that the UPS and battery have been successfully tested together. Even with that, testing under site conditions should be included in the equipment-commissioning plan.

Specifying

One of the roles as an original equipment manufacturer of UPS systems includes assisting and guiding end users as to the correct application of the UPS and battery system(s). We also assist with interpreting specifications and capabilities very early in the acquisition process. Today the total cost of ownership, time of service, time between service, and lifecycle considerations published incorporate changes from classic lead-acid specifications and application guides. Starting with service life, lead acid systems tend to have a non-linear, nearly exponential degradation as they wear out in the last 20 percent of their service life. Our previous papers on this topic for VRLA units documented the difficulties with forecasting service lives, even with a portfolio of millions of units. Li-ion battery manufacturers today are claiming a nearly linear degradation of 1-2 percent per year. This means that battery capacity starts dropping immediately after startup. The impact of reduced capacity is felt and observed during the entire service life of the battery rather than being heavily weighted near the end of life. For example, a battery with expected 15 year life and 20% reduction in capacity: At year five the Li-ion battery will have lost about 7% capacity. We recommend that specifications request a statement of the battery operating time at the specified load at the end of life.

Our position is that monitoring Li-ion battery systems is mandatory to determine if the battery capacity degradation is following the expected rate. Li-ion battery monitors often include a reported value of capacity, which with remote monitoring can track the other critical battery characteristics. Any deviation from expected capacity should result in review of the monitored battery data to determine what may be causing the deviation.

Field Installation

Field Installation of Li-ion battery systems vary from the so-called "rack and stack" to fully preassembled cabinets. During our evaluation and release process, we learned and appreciated the weight and footprint reduction of Li-ion battery units. Every Li-ion battery system is equipped with a battery management system (BMS). The required integration of a BMS requires field labor expertise beyond more typical lead-acid battery installation. There are five integration points between the Li-ion battery and other systems our application:

- Li-ion battery module communications to Li-ion battery string level electronics (a BMS component)
- Li-ion battery module to Li-ion battery module
- Li-ion battery string BMS to full system BMS (when included)
- Li-ion battery to UPS
- System BMS to building management system, monitoring and historian systems.

Li-ion battery manufacturers have all designed a hierarchical (tree) management system that starts with units and at the top provides open communications. Within each level are closed loop controls comprised of hardware and software to permit it to function within a series or parallel string or community of units. The paradigm discussed previously of fail-safe operation permeates the core design of Li-ion battery systems. Whereas previous technologies and chemistry would serve their primary function (deliver DC energy), even when risking their own internal damage, keeping the power "up" was primary. With previous systems there were no safety implications of abusing the battery systems through minor excursions of voltage or temperature. Li-ion systems report unit-based data, aggregate this data and then provide it on their communications buss. At the lower levels of the architecture these connections today are closed, proprietary and utilize connections provided by the unit manufacturer. Typically, each unit then communicates upward to a cabinet and/or string level communications aggregation point. Once again, with a paradigm of failing safely as a priority, the aggregation system monitors charge and discharge currents in and out of the string, over and under battery voltage and battery cell temperatures. The cabinet or string aggregator and battery management system together must function within requirements for the battery to be connected to the UPS system. Communication to external monitoring is typically Modbus/485 or Ethernet through direct physical connections.

Unlike previous technologies, Li-ion battery systems protect themselves, and then after the fault or exceeded limit has ended the string must be brought back online manually. The timing to allow this reconnect can be several hours in the case of over temperature of a cell, particularly if the enclosure or room temperature is elevated.

On Site Acceptance

Once installed and communicating, onsite acceptance processes are similar to a VLA or VRLA system that also incorporates a permanent stationary battery monitoring system. As the number of total units and strings can vary it is important to validate that the actual recharge current of a fully installed and commissioned system does not overload through current limitations, the UPS's recharge capabilities. The available data, telemetry, temperature sensing and operating mode communications provides comprehensive data to assist with validation through the battery management system's communications interface. Protocols such as Modbus/IP provide an open interface to store performance data for comparison against baselines, manufacturer specifications and for future subsequent analysis.

Operation and Managing Failures

Over the full lifecycle of the Li-ion battery system it may be necessary to replace one or more units. We have found Li-ion battery systems generally are very tolerant of mixing new cells and new units with aged ones. Most importantly, the aggregation and controls systems demand that the unit count and cell count never change within a string. Past practices of "jumpering" out a temporarily removed unit and adjusting float voltages are not possible. Replacement battery modules should be readily available either by spares on site or available for overnight shipment. The new unit will typically arrive or be charged to approximately 30% of capacity. Any new unit must be charged to the capacity of the other or discharged to match the voltage of the other units in the string. A single unit with low capacity will not significantly increase in capacity under float charging conditions if simply added to a string.

Services

Unlike previous technologies [4], the battery units themselves internally consist of cells, electronics, software and communications. Updates to embedded firmware, revisions to electronics and interfaces and updates to local aggregators are to be expected. Additionally, those interactions with external systems including alarm systems and data storage systems result in the likelihood of required security updates and user interface updates. Physical inspection of the unit's condition, safety mechanisms and communications modules require periodic inspection as do other critical electronics systems. Since battery management systems have limited storage capabilities, they require a data store and historian to preserve environmental and performance data and to confirm to manufacturers that operational requirements are met.

End of Life Consideration

As detailed above, the expected linear wear and the ability to mix and match aged units within a string permits more flexibility that enables a condition and performance based maintenance approach. Once a unit or string is deemed unserviceable for the application, re-task, rebuild or recycle are options. One publicized reuse of vehicle LIB systems [5] for home stationary applications represents a model we expect to be extended from stationary service units. This reuse model re-tasks units for less critical use to extend their utility as a ready to use component. A second emerging reuse is disassembly of units to retrieve cells and essentially rebuild units for other applications.

Monitoring and Data Analysis

Each installed Li-ion system operates autonomously with safety and service life as its primary mandate. Some of our challenges during integration with UPS systems, monitoring systems and data analysis systems included not only knowing the state of the battery system, but how it arrived at that state. For example, if during a series of discharge events one unit (or one cell) exceeded its maximum operating temperature, the battery management systems would disconnect the battery string from the DC link so that a cool down process can begin [6]. Later, when temperatures return to normal the units may be manually reconnected, some manufacturers are naming this "self-healing". By integrating an external management, historian and analysis system with the battery management system Li-ion users can understand what occurred over time, in the sequence it occurred and correlate with power and load associated on the battery string, units and cells. As mentioned previously, we are pleased with the rich data content; in time, we will use this information to anticipate and avoid both short and long-term disruptions of service, and avoid costly, time-consuming investigations to determine root causes for alarms and failures.

Proper monitoring of the cells within a unit and units within a string enable a long service life with the lowest operational risk. These external monitoring systems aid with identifying and diagnosing abnormal battery operation allowing replacement of failing components while preventing unexpected loss of a battery string. We are encouraged by the available information from units at the cell level. Although an external system is required to store, analyze and retrieve data, this built in ability to publish information on actual, rather than manufacturer estimated performance provides insights into the health of each cell. We enjoy a large, diverse user installed base and learning more about the operational results and operational precursors will allow better forecasting of imminent failure in the future

Finally, at least one provider has technology which is capable (albeit with modifications to the unit) of early detection of failing cells due to outgassing within a unit [7]. In lab environments, this has proven to help end cascading failures.

Conclusion

Li-ion units, strings and battery management systems represent a new class of challenges to UPS original equipment manufacturers, particularly when the energy source incorporates its own software and hardware. These challenges represent a shift from the long-standing paradigm of lead-acid units since the Li-ion battery unit protects itself above providing energy to the UPS system. Over the next few years, we will learn much about how this new battery performs in UPS service.

Works Cited

[1] Underwriters Laboratories, "UL 1973: Standard for Batteries for Use in Light Electric Rail (LER) Applications and Stationary Applications”," no. Ed. 1, 2013.

[2] Underwriters Laboritories, ""Standard for Software in Programmable Components"," *Underwriters Laboratories,* vol. Ed. 3, 2013.

[3] Underwriters Laboratories, "“UL 991: Standard for Tests for Safety-Related Controls Employing Solid-State Devices”," vol. Ed. 3., 2004.

[4] Vertiv Company, ""The Effect of Regular, Skilled Preventive Maintenance on Critical Power System Reliability"," November 2007. [Online]. Available: www.vertivco.com. [Accessed 2 April 2017].

[5] Woodyard, "“C. Lithium-ion battery project is worlds largest”," *USA Today,* 16 September 2016.

[6] N. C. F. S. V. S. M. Ponchaut, "“Thermal Management Modeling for Thermal Rundaway Avoidance in Lithium-Ion Batteries”," in *Battcon*, Boca Raton, 2017.

[7] Nexceris,, ""Lithium Ion Battery Safety Systems"," 2017. [Online]. Available: www.nexceris.com. [Accessed 3 March 2017].

[8] Underwriters Laboratories, "“UL 1642: Standard for Safety-Lithium Batteries”," vol. Ed. 5., 2012.