Thought leadership
White paper

Lithium batteries for UPS applications

Battery management and chemistry choices pave the way

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Figure 1: Lithium-ion battery

Powering Business Worldwide

Executive summary

Historically, the battery of choice for UPS applications has been a valve regulated lead acid (VRLA) model. Nickel cadmium (NiCad) batteries, which have probably been around for longer than VRLA batteries, are also a good choice for certain applications. Other than these two chemistries, there has not been another battery choice until recently, in the last five to eight years, when a third choice, lithium chemistries, has become commercially available for UPS applications. The purpose here is to review the properties of lithium batteries that are important for UPS applications.

Traditional UPS applications are characterized by infrequent transfers to battery and relatively short discharge times when they do occur. This is typically referred to as a float service application as opposed to a cyclic one. Three factors set UPS applications apart from others. The first is the battery load presented by the UPS, a constant power one. It is quite stressful or demanding for a battery, because the current must increase near the last part of the discharge as the voltage starts to decrease in order to maintain the product of voltage times current a constant. The constant power load on the battery creates a kind of race to the bottom (cutoff voltage). As the voltage decreases, the current must increase (i.e., increase in discharge rate), which causes the voltage to decrease even more, causing the current to increase again and continuing until reaching the cutoff voltage. All this occurs when the battery has less and less active material available to participate in the discharge.

The second and third of these factors are short discharge times, in the range of 1 to 10 minutes, and the high current typically drawn from the battery during a discharge. For UPS applications, the battery is typically sized for the specific discharge time required plus a small margin. This is done primarily to minimize the cost of the battery, but also to minimize the footprint taken by the solution. Now, as a result of minimizing battery size, the current drawn during the discharge is usually quite high.

Taken together, a demanding load presented to the battery and the fact that the UPS wants to remove as much charge as possible as fast as possible, require the battery selected for a UPS application to be optimized for all three factors. The importance of these is quickly confirmed when exploring the characteristics of other battery chemistries for UPS applications.

TABLE 2.2 Relative merits of selected commercial Li-ion battery cathodes

Advantages	Disadvantages
LMO ($LiMn_2O_4$ and variants)	
Low cost	Mn solubility issue, affecting cycle life
Excellent high rate performance	Low capacity
High operating voltage	
No resource limitations	
Moderate safety (oxygen release)	
LFP ($LiFePO_4$ and variants)	
Moderately low cost	Low operating voltage
Excellent high rate performance	Lo capacity, especially for substituted variants
No resource limitations	Controlling patents
Very slow reaction with electrolyte	
Excellent safety (no oxygen release)	
NMC ($LiNi_{1/3}Con_{1/3}Mn_{1/3}O_2$ variants)	
High capacity	High cost of Ni and Co
High operating voltage	Potential resource limitations
Slow reaction with electrolytes	Relatively new in performance
Moderate safety (oxygen release)	Controlling patents
NCA ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$)	
Performance is well established	High cost of Ni and Co
Slow reaction with electrolytes	Potential resource limitations
High capacity	Controlling saft patents
High voltage	
Excellent high rate performance	

Figure 2

Focus on lithium

There are many choices of lithium chemistries and cell designs that could potentially be used in UPS applications. Properties of these chemistries can best be shown and compared using the chart in Figure 2 on right. Recall from above one of the three characteristics of importance for a battery in a UPS application is high rate performance. When selecting a chemistry and sizing a battery, the current handling capability directly controls the number of parallel strings needed, independent of the required discharge time. From Figure 2, then, the most promising choices would be lithium-iron phosphate (LFP), lithium-nickel-cobalt-aluminum (NCA) and lithium-magnesium oxide (LMO).

Another criterion for selecting a lithium chemistry is safety. The primary concern here is the occurrence of thermal runaway. Overcharging, over-discharging, excessive discharge current or an internal cell defect can push a lithium battery into thermal runaway. With some chemistries, a thermal event will be significantly more intense than others. Temperatures in excess of 300°C to 500°C can be reached in a short period of time when thermal runaway occurs. The heat generated and the temperatures reached can, in some cases, auto-ignite adjacent cells, causing the damage to spread even further. The reason for the intense heat generated is some chemistries release oxygen at temperatures within the range of the thermal event. This oxygen then becomes fuel that will sustain the burning.

Referring to Figure 2 again, it is clear that LFP chemistry does not release oxygen (at the temperatures experienced) during a thermal event and thus will be a safer choice than the others. For most UPS applications, the choice of LFP has not required sacrificing the other characteristics important for lithium chemistries, notably float service life and reduced footprint. Another choice for safety, although not readily available for commercial applications, is lithium-titanate oxide or LTO. This chemistry has the potential to perform even better in high discharge rate (i.e., high current) applications.

There are some benefits to using a lithium battery in a UPS application when compared to a VRLA battery. Chief among these is a lithium battery should provide a longer float service life, even at high discharge rates. Most lithium battery manufacturers have not performed the traditional accelerated float service life testing as is done for VRLA batteries. As a result, many try and estimate the float service life from cycle life testing. The problem with this approach is a cycle life test can be performed over a time period of just a few months, which is not sufficient aging time for other life controlling mechanisms to appear. One might wonder what the cycle life might be if it was spread over the expected float service life of the battery. This is more in keeping with a typical UPS application, where outages of more than a few seconds duration are not too frequent. In spite of the lack of test results, most lithium manufacturers believe the float service life will be in the range of 7 to 10 years in high-discharge rate applications.

Another benefit of using a lithium battery is reducing the footprint or volume as compared to an equivalent lead-acid (Pb-acid) solution. Battery footprint is important in many applications where floor space is at a premium. In a rack application, it is safe to say no one wants to give up space for the UPS and battery. A smaller footprint or lower volume is not always automatic, depending on the power level and discharge time of interest. Great care in packaging of the cells and the battery management system (BMS) is required to achieve or demonstrate this benefit.

Still another reason to choose lithium is charge times are shorter. This is due to the higher charge efficiency of the lithium chemistry compared to Pb-acid. Charge times in the range of five to six hours or less have been obtained over a range of discharge times that are typical for most UPS applications, with relatively low charge currents on the order of 0.55 C. In most parts of the world, where the grid is quite stable and reliable, this may not be a deciding factor for using lithium.

Finally, a lithium battery will have a longer shelf life than some of the Pb-acid models used in today's UPS battery systems. However, pure Pb, with a shelf life of 24 months, is still as long as or longer than a lithium chemistry. The self-discharge rate of both lithium and Pb-acid is approximately the same. The reason a lithium battery has a longer shelf life is it can self-discharge to a greater depth of discharge (DOD) than Pb-acid and still be recovered (i.e., recharged) to the rated capacity. Balancing the cells, which is done every time the system is started, may take longer after a prolonged period of storage. To obtain a long shelf life with a lithium battery, it is necessary that the BMS is not operating while the battery is being stored. The current drain of the BMS can be of sufficient magnitude to discharge the battery rather quickly compared to the self-discharge rate. Many of today's manufacturers have means to either disconnect the BMS or put it into a sleep mode, where the current drain is small relative to the self-discharge rate.

Like most things in life, there are characteristics of lithium batteries that are not considered benefits and must be dealt with when designing or selecting a battery system for UPS applications. Lithium chemistries are not very tolerant of operating conditions outside the recommended limits. Small departures of the float voltage above the maximum recommended (overcharging), discharging below the minimum cutoff voltage (over-discharging) and exceeding the maximum temperature rise of the cell either from ambient conditions or from too high a discharge or charge current can all induce thermal runaway. This is generally a catastrophic event for most lithium chemistries, with the exceptions being LFP and LTO. Contrast this with a Pb-acid VRLA battery, which can also be put into thermal runaway, but is more tolerant of the operating conditions. That is, high discharge or charge currents and over-discharging will not start the battery on a path to thermal runaway — although there can be a reduction in the discharge time and/or float service life. Overcharging a VRLA battery or using it in a high ambient environment can bring on thermal runaway.

The role of the BMS

As a means of protection, most lithium battery systems of almost any string voltage require a battery management system (BMS) to maintain the cell operating conditions within the limits. These can range in complexity from just cell balancing to ones that monitor cell voltage; cell temperature and current; and, through the use of either semiconductor switches or relays, will disconnect the battery pack from the UPS if any of the monitored variables exceed their operating limits. When interfacing a lithium battery system to a UPS, it is vital to know and understand the limits at which the BMS will disconnect the battery. Many of the BMSs will provide a warning if the operating conditions are approaching these limits before any action is taken. In this manner, it is possible to take some action to avoid having the battery disconnect from the UPS. The BMS will generally not reconnect the battery until the conditions that caused the action are removed. A second reason for having a good understanding of the limits is to make certain the UPS, in normal operation, will not exceed them. Taking care to verify the limits will not be exceeded by the UPS is a good practice and good system design.

The following is a brief description of the functions contained in a typical BMS. The first of these is cell balancing, either passive or active. The purpose of cell balancing is to maintain the terminal voltage of each cell, or bank of parallel cells, in the series string approximately equal. Since cell voltage bears some relationship to capacity, with lithium chemistries, keeping these equal will tend to maintain the capacity of each cell equal. This then will serve to prevent weaker cells, those with lower capacity, from being over-discharged. Likewise, cells with higher capacity will not become overcharged. The importance of cell balancing can be seen in Figure 3. Here, a discharge and charge cycle of two LFP packs containing 12 cells in series and 3 in parallel (12S3P) is shown.

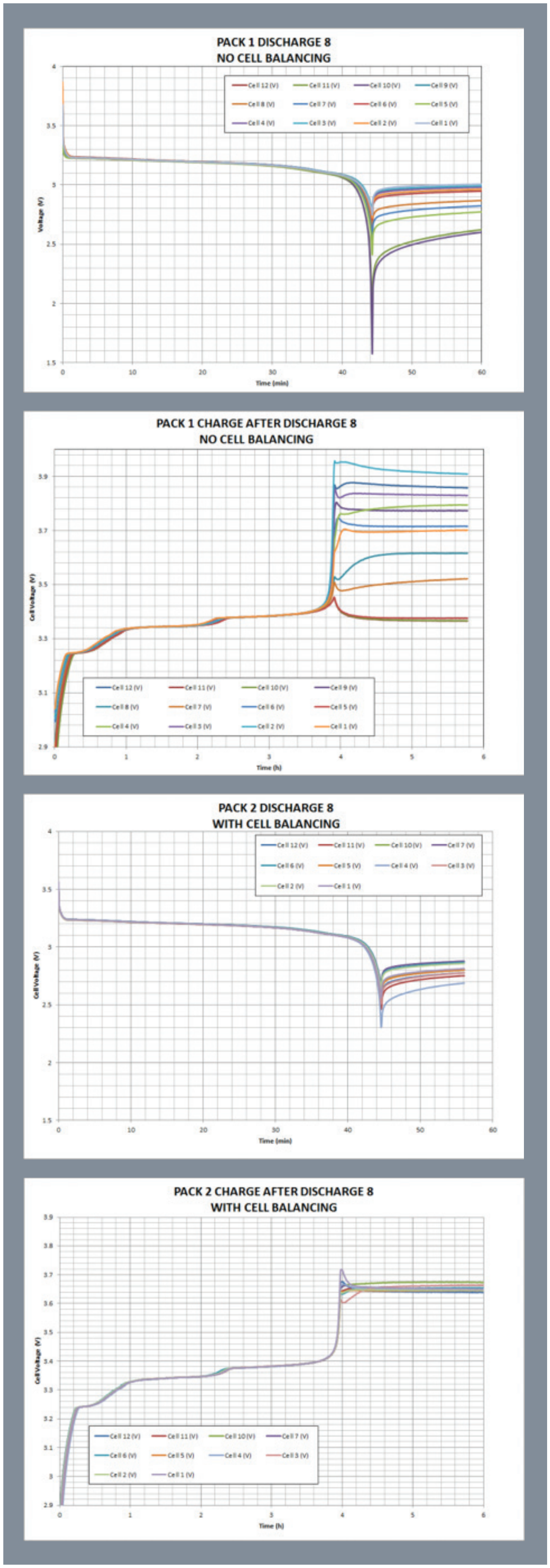

Figure 3

On the discharge plots, note some cell voltages in the pack with no balancing decreased below 2.0 V, the minimum limit, near the end of the discharge. This is over- discharging and was starting to occur after only the eighth cycle. In the pack with cell balancing, the voltage decreased to 2.5 V for most of the cells, with one reaching 2.3 V before the discharge ended. All cells are substantially above the 2 V limit.

During charging, after the eighth discharge, note the spread in cell voltages of approximately 0.59 V for the pack with no cell balancing. One cell nearly reached the float voltage limit of 4.0 V. Above this limit is overcharging. With the pack containing cell balancing, the cells are tightly grouped around the float voltage of 3.65 V. The spread in cell voltages will continue to increase as more discharge/charge cycles are accumulated.

Next are what may be called the measurement functions. Cell voltage, as shown in Figure 3, is one of these. The purpose of this measurement is to make sure the cell voltages are close enough to each other that the battery can be charged and discharged over the intended range of operation. In some instances, the BMS may not allow charging or discharging, at least not at rated load, until the cell voltages are within some predetermined range of each other. Another measurement is current through the cells. There are usually maximum charge and discharge current limits that if exceeded will trigger a warning and possibly disconnect the battery from the UPS if the condition persists for some prescribed period of time. The third measurement is cell temperature. When evaluating a battery system for use with a UPS, it should be a requirement that the case temperature of one or more cells is measured. Due to the rapid rise of temperature in the case of a thermal event, an (internal) air temperature measurement may not be fast enough, or sensitive enough, to detect the onset of thermal runaway and take action to disconnect the battery. The BMS will protect the battery from excessive temperatures by signaling when the cell temperature is nearing or has reached the maximum and ultimately disconnect the battery from the UPS if the maximum is reached. Other action that is sometimes taken by a BMS is to limit or postpone charging of the battery until the temperature has decreased sufficiently from the limit.

Some BMS models may also provide a measurement of state of charge (SOC) and an indication of the state of health (SOH) of the battery system. The SOC is obtained by measuring the charge, in Amp hours (Ah) removed (discharging) and replaced (charging). Charge is usually measured by integrating the current into or out of the battery with respect to time. Starting with a known value of available charge, the SOC is just the ratio of the net charge (discharged Ah – charged Ah) to the available charge. With some lithium chemistries, the cell voltage provides a reasonable indication of the SOC. The SOH is an indicator of the amount of degradation or aging that has occurred since the battery was new. The basic approach is to determine how much the available charge is decreasing with age. A test discharge, starting from the fully charged state, is usually used to make this estimate. Capacity loss as the battery ages is sometimes referred to as capacity fade.

Another aging mechanism that can occur with some chemistries is referred to as power fade. This is of more concern in high discharge rate (i.e., high current) applications, such as a UPS. Power fade is a result of an increase in resistance of the cell as it ages. With high current discharges, the increased resistance causes the cell voltage to decrease and thus reach the cutoff voltage earlier. The end result is a shorter discharge time. Some BMSs have the means to make a resistance measurement and estimate the decrease in discharge time.

Focus on heat

Of considerable importance when developing a battery system for a UPS application is the heat generated in the cells during charging and discharging. Lithium chemistries are exothermic on charge and discharge. That is, the reactions themselves release heat as a byproduct. This is in addition to the heat generated from losses in the connections and wiring, sometimes referred to as joule heating. The additional heat generated from these reactions must be managed to prevent the cell temperature from exceeding the limit above which permanent degradation of the cell will occur, possibly leading to thermal runaway.

In a general sense, it is desirable, regardless of the rating of the battery system, to avoid using fans for cooling. A fan adds cost to the pack and potentially increases the volume of the system as space for both the fan and airflow must be created. And finally, a lithium battery system is expected to last up to 10 years in a float service application with no maintenance. Adding a fan that has a fixed life, generally shorter than that of a lithium battery, nullifies one benefit of choosing a lithium battery solution. Passive cooling of the battery system is preferred and will be successful for most UPS applications operating in controlled environments.

Conventional techniques such as spacing between cells and allowing some airflow through the system help, and are necessary, but generally are not sufficient at the high discharge rates of most UPS applications. One choice is to oversize the battery by adding parallel strings. Since the heat generated from the reactions is a function of the current, the temperature rise of each cell will be less when more parallel strings are sharing the current. The downside of this choice is the cost and volume consumed of the solution will increase. The discharge time will increase also, which may or may not be desirable.

Increasing the number of cells in series can also help reduce the temperature rise of the cell. Recall that the load placed on the battery by the UPS is a constant power one. Increasing the number of cells used translates into lower power being taken from each cell. This can also be explained by noting that increasing the number of cells in series will increase the operating voltage of the string. Noting again the load on the battery is constant power, $P = E \times I$ = a constant. Then if the voltage, E, increases, by necessity the current, I, must decrease. A lower current generates less heat.

A third means to manage the heat, one that has the potential to not increase the cost, is to modify the cutoff voltage based on the battery load and local ambient temperature. With many designs, the available discharge time is longer than the desired discharge time. Raising the cutoff voltage when the battery load is high shortens the discharge time, and thus the cell temperature will not reach or exceed the maximum limit where the pack disconnects itself from the UPS, or worse, degrades the battery. The same approach can be taken by sensing the ambient temperature around the battery system. It should be noted that this method requires some characterization of the battery system to determine the specific cutoff voltages that should be used to limit the temperature rise of the cells.

The takeaway

Overall, a lithium chemistry battery system can be a good choice for some UPS applications. Selection of a particular chemistry should be made with safety in mind as well as the other system requirements, namely float service life, footprint or volume of the solution and discharge time. An understanding of the functionality of the BMS is important to verify the battery will be adequately protected in its intended application and environment. It is beneficial if the system designer can exercise some influence over the number of cells in series and number of parallel strings, together with the cell manufacturer, to optimize the battery design for the specific UPS operating conditions. Finally, it is of paramount importance to manage the heat generated during charge and discharge, so the temperature rise of the cells is maintained below the maximum limits set for that chemistry.

References

1. Brodd, R.J. (2013) Batteries for Sustainability, Selected Entries from the Encyclopedia of Sustainability Science and Technology, Chapter 2, Battery Cathodes by M.M. Doeff, pg. 12

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