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Lithium Ion Battery Packs

High Power Usage and Control

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The safe and effective use of lithium ion battery packs requires consideration of their electrical and thermal characteristics. This article discusses the factors limiting the maximum charge and discharge rate, including temperature effects. This discussion highlights the opportunities for sophisticated electronic measurements to aid in controlling battery packs and providing users with useful information. In addition to knowing the most recent ability of the pack to provide capacity, it is now possible to know the state of health with respect to discharge rate. Electronic controls not only improve performance but may also prevent thermal runaway in some cases of abuse.

Maximum Charge Rate

The charge rate of a cell is limited by its maximum allowable charge voltage, impedance and temperature. The maximum allowable charge voltage is based on the maximum allowable open circuit voltage (OCV). For many lithium-ion cells, the OCV indicates the state of charge (SOC) of the cell; for example, see Figure 1. Currently, the industry standard is to consider a cell fully charged that has a voltage of 4.2 V.

The 4.2 V standard was arrived at by experience and is a balance between maximum capacity per gram of active positive material and its thermal stability. Most chargers in the field that use this voltage standard tend to demand that all materials use the standard whether or not they are more or less stable. The typical positive material is lithium cobalt oxide ($LiCoO_2$). Lithium manganese oxide ($LiMn2O_4$) (aka spinel) has been shown to have a higher thermal stability as a material but as a system in a commercial cell, it is considered to be so similar that the voltage standard still tends to be 4.20 V. Some newer cells can be charged to voltages above 4.20 V, but these cells have not yet been proven commercially.

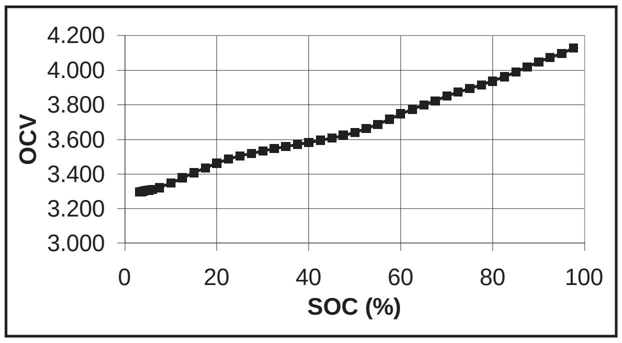

Figure 1. OCV versus SOC

As the cell charges at some current (I), the closed circuit voltage (CCV) reaches 4.20 V before the OCV does because of cell internal impedance (R).

$$CCV = OCV + IR \qquad (1)$$

Typical initial charge rates tend to be 0.5C to 0.8C. C-rate refers to the current required to charge the cell in one hour, so a 0.5C rate would charge a fully discharged cell in two hours. However, the higher the current, the sooner the CCV limit of 4.20 V is reached. When the 4.2 V CCV limit is reached, the cell current must decrease to prevent overcharging the cell. This type of charging is referred to as constant current/constant voltage (CC/CV) charging. During the CV phase, the current decreases until some low cutoff value is reached (typically C/20).

To appreciate how the maximum charge rate is limited by the 4.2 V CCV limit, consider a 2 Ah cell with an impedance of 0.13 ohms. If the initial SOC is 25 percent (OCV=3.5 V), then the maximum initial charge current is 5.4 A. Figure 2 shows another example over a wide range of conditions.

Figure 2 shows the charge rate versus SOC for the standard 4.20 V. All the curves come together as they increase in SOC. By extending the curve back to zero SOC, one can see that even at very low SOC, the current would not exceed 2,400 to 2,600 mA. In this case, the impedance of the cell limits the maximum charge rate to about the C-rate. Even if the designer reduced the cell impedance in half, the cell could not be charged (at 2C) in less than about 30 minutes. This example shows how the 4.2 V CCV limit and the cell impedance bound the maximum charge rate. However other factors also limit the charge rate.

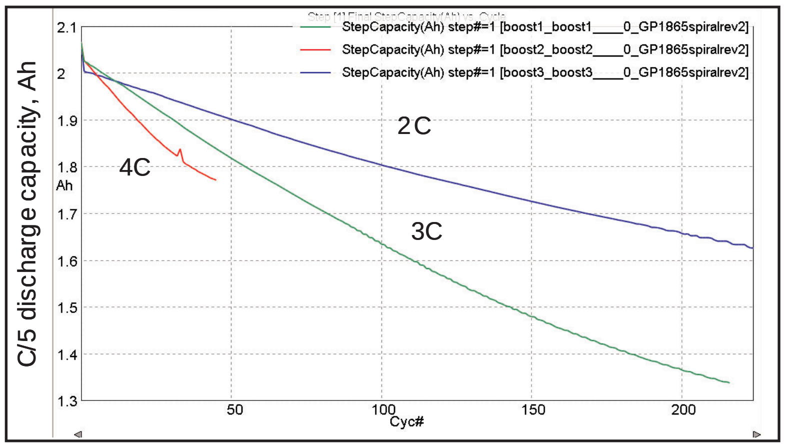

Figure 2. Charge rate versus state of charge at various initial rates (ma) all subject to a maximum cell voltage of 4.2 V

Lithium Plating at High Rate and SOC

There is another more difficult way to measure limit to charge rate. The negative electrode can start forming metallic lithium on its surface at high charge rates well before the end of charge and even when the cell is being held below 4.20 V. Metallic lithium formation should be avoided because it will shorten the life of the battery. Metallic lithium will react will the electrolyte and become deactivated. The result is permanent capacity loss. As a benchmark, typically, 20 percent of the cell capacity is lost at 300 cycles, from all causes using 0.8C/4.20V CC/CV charging for 2.5 hours.

Boost Charge Losses

Boost charging is a method by which the initial charge current is very high and then reduced significantly before the cell hits the 4.20 V limit.

Figure 3 shows a comparison of boost charge rates which correlate high charge rate with high rates of capacity loss. The most interesting rates include:

a) 2 C for 10 min, 0.8C for 50 min., limited to 4.20 V, 18 to 22 percent loss in 200 cycles

b) 3 C for 7 min, 0.8 C for 53 min., limited to 4.20 V, 25 to 35 percent loss in 200 cycles

There are many alternative ways to charge cells. By programming the charger to do short pulses at high rates, it is expected that charge times below one hour at 95 percent SOC can be achieved at low loss. Therefore there is need for smart chargers when it comes to fast charging.

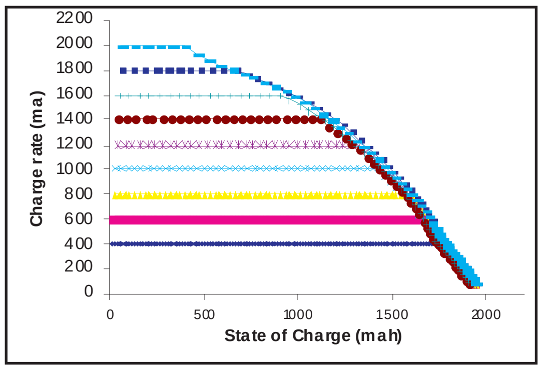

Figure 3. Boost charging schemes. Discharged cell is rapidly charged to 35 percent SOC, then fully charged at lower rate.

Low Temperature Charging

The typical low temperature charging limit recommended by battery manufacturers is 0°C. Experiments have shown that charging at lower temperatures results in permanent capacity loss due to metallic lithium formation at the negative electrode. The maximum allowable charge rate at 0°C seems to be about 0.1C. Commercial chargers typically do not account for charge temperature. Users should be encouraged to charge at room temperatures to avoid heavy capacity degradation. Here is another opportunity of makers of smart chargers to adjust the maximum initial charge current lower as a function of temperature.

Discharge Heating

Small packs with cells in a single level, with respect to diameter, tend to have the ability to reject heat similar to a single cell, or at least within 50 percent. As the pack grows larger and multiple rows of cells are used, the relatively small percentage of energy stored in the pack lost as resistive heating, can raise the pack temperature to levels in which the electronics must shut the pack down. For example, BB-2590 packs with 24 cells are widely used in the US Army to power communications equipment. The internal temperature of these packs can reach over 70°C when discharged at the 1C (6 amps), whereas the temperature of a single cell discharged at 1C would not exceed 45°C. Many packs are used in such a way that external cooling cannot be provided. The only practical way to prevent overheating is to limit heat generation by using cells and electronics with very low impedance. Adding conductive material to the cell to reduce impedance can reduce the available volume for capacity by as much as 50 percent. For example, cells used in very high rate applications like power tools have significantly lower capacity than higher impedance cells used in many portable electronics applications.

Entropy Effects on Pack Temperature

The $LiCoO_2$ chemistry releases electrochemical heat on discharge and reabsorbs it on charge. This amount of energy can be converted and stored as electrochemical energy and then rejected as heat is equivalent to the entropy of the chemical reactions. In purely thermal processes, entropy is a portion of the chemical energy that cannot be converted into work. Batteries are a special case in which this energy can be absorbed from the environment and converted into work. So when the battery is charged a very small amount of heat energy absorbed from the environment is converted in to electrical work. Upon discharge some of the energy is rejected as heat and the battery heats up more than it would have without this effect. In order to illustrate this effect, a BB2590 was charged and discharged at constant current to maintain a constant I^2R power loss. So the difference in temperature rise is a measure of the entropy change. If the entropy change were zero, then the charge and discharge temperature curve would converge to approximately the middle of these two curves. The amount of entropy change can be chemistry dependent. Some $LiNi_{(1-x)}Co_xO_2$ chemistries have a low level of entropy change. Figure 4 illustrates the difference in charge and discharge temperature rise for cobalt oxide. Current rate is constant on charge and discharge.

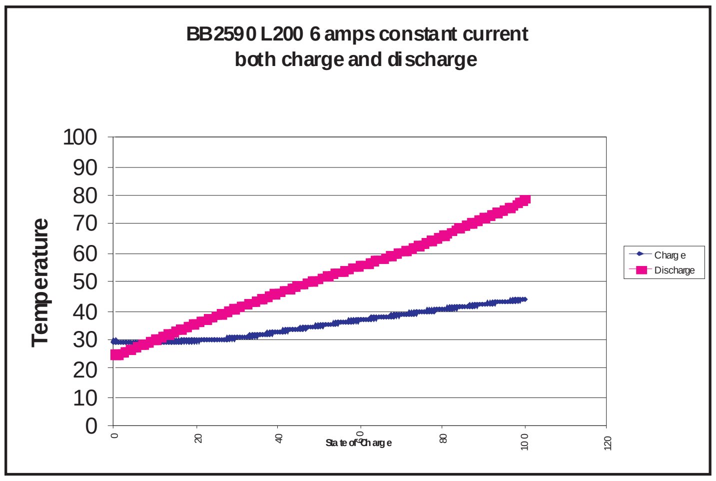

Figure 4. Charging of large pack and difference between charge and discharge

Thermal Design of Components

Large packs need to carry a lot of current. Some components are small so the heat flux may be high. With dead air conditions in the pack and possible thermal isolation of the component, relatively high temperatures can be experienced.

An example numerical analysis shows that the control FETs are getting pretty hot. The example is for a BB-2590 discharging at C-rate or about 6 amps. This simulation was done by Battery Design Co. for Gold Peak Industries (NA) Inc.[1] Figure 5 shows the discharge FET exceeding 162°C. (i.e. white color) A FET with higher current capability is probably needed for this rate of discharge.

Cell Balancing

Cell balancing with pack electronics can provide advantages. The main advantage, in a pack situation, is that the cell strings never exceed the manufacturer's recommended maximum charge voltage. Charge voltages in excess of 4.20 V can accelerate the degradation of cell capacity. Chargers normally control only the total charge voltage. Cell imbalance can allow some strings to exceed 4.20 V while other strings fall below. This probability starts with two cell strings and increases with the number of strings, typically no more than four strings. The origin of cell imbalance is due to a few factors. One is that the cells have different capacity. Not much can be done in this case and the cell manufacture should control or ship their cells with matched capacities. Typically the manufacturer does 100 percent capacity testing so this is a material handling issue. One warning in this respect is that some pack manufacturers request OCV matching from the cell manufacturer. If the origin of OCV difference is a range of cell capacities then OCV matching does nothing to solve the problem. In this case, the cell manufacturer discharges all the cells to zero and put a constant input (mAh) in to the cells. If the cells have a range of capacities then they will have a range of SOCs. This may be the cause of the OCV spread. So the cells need to be capacity matched before OCVs are matched.

Another source of imbalance is that the cells are degrading at different rates. Again, not much can be done by the user to affect this other than insure that the manufacturer ships cells from the same lots that have similar loss characteristics.

The most common reason of cell imbalance, that will be experienced by the user and can be fixed by electronics, is the slow loss of charge due to self-discharge of the cells. Typical self-discharge rates are less than 1 percent per month or about 100 microamperes in an 18650-size cell. On the other hand, this rate of loss can accumulate over time. As cell strings are allowed to exceed 4.20 V, due to imbalance, they start to experience permanent capacity loss, for reasons noted in the first part of this article. There is no compensation for capacity degradation but cell balancing can remove one of the most common sources of capacity degradation. In extreme cases, where there are other sources of internal imbalance in the cell and/or there has been some physical abuse in addition to loss of string balance, a situation may arise to create thermal runaway due to shorting. Some pack makers have created their own discrete electronics for cell balancing. Texas Instruments now makes safety chips with integrated cell balancing and measurement of string impedance, which is a comparatively low cost solution.[2]

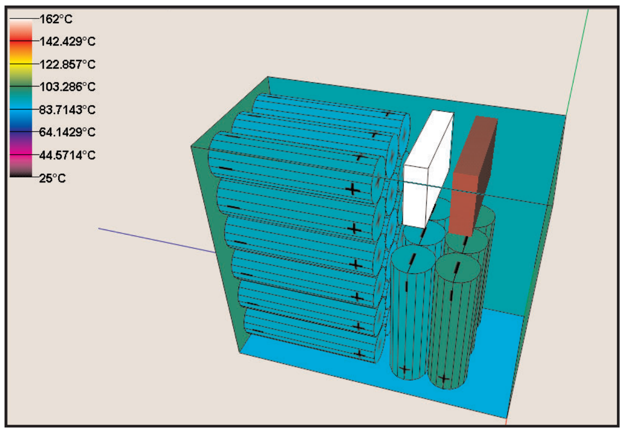

Figure 5. Temperature distribution in a battery pack. The rectangular-shaped objects are FETs.

State of Health

The measurement of string impedance provides the battery designer with a measure that indicates the state of health (SOH) of the battery. Capacity is the most common measure and can be tracked with many versions of pack electronics. The loss of capacity and especially capacity at high rate is better estimated with the measurement of string impedance. A pack may have not lost much capacity at low rate discharges but an increase in impedance can predict that the pack will not perform to expectation at high rate. A high impedance pack may lose sufficient operating voltage to operate the device.

Summary

There is a variety of electrical and thermal limitations for Lithium Ion battery packs. In some cases there are electronic solutions to these problems and in other cases these limitations represent opportunities for the increased use of electronics.

Reference

[1] "How to Charge Lithium-Ion Batteries: An Assessment of Approaches Using Computer Simulation", Proc. of Advances in Battery Charging, Monitoring, and Testing, Denver, Colorado, August 18, 2004. www.batdesign.com

[2] Texas Instruments, Data Sheets, www.ti.com

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