An Investigation of Cell Balancing and Equalization for Lithium-Ion Battery Packs

Stephen W. Moore, P.F. Stevens

Abstract

The requirement for cell balancing and equalization for lithium-ion battery packs is studied. Since lithium-ion battery cells lack an intrinsic ability to dissipate excess charge energy, artificial means are required to balance and equalize cell voltages in series strings. Cell balancing electronics that are oversized may result in faster balancing times but at a higher cost. Insufficient cell balancing will eventually lead to lower usable pack capacity and failure. This paper investigates some requirements for cell balancing mechanisms and the resulting battery pack performance effects. Data representing thousands of cycles from battery packs is presented and the effect of equalization time and current is presented.

Keywords: Battery Management, Charge Equalization, Cycle Life, Lithium-Ion, Secondary Battery

1 Introduction

Lithium-based secondary battery technologies offer performance advantages over traditional battery technologies at the cost of increased monitoring and controls overhead. The nature of lithium batteries necessitates tightly controlled voltage and current operating conditions. Multicell series connected lithium battery systems present a design challenge to create an optimally performing energy storage solution.

Lithium based batteries are intolerant of overvoltage, which can result in cell damage or decreased performance [1-4]. Charging must be controlled to avoid overvoltage of any individual cell in a series-connected battery pack system, or shortened battery life may occur.

Unlike traditional lead acid [5,6] or NiMH [7] batteries, lithium based chemistries do not have a natural cell equalization method. The lack of a natural equalization method in multicell lithium battery packs can result in unbalanced cells. Without controlled artificial balancing, individual cell State of Charge (SOC) will deviate from the average SOC of the pack.

Even though the pack voltage may appear to be within acceptable limits, some cells within a series string may experience overvoltage due to cell-to-cell imbalances. This is illustrated on Figure 1. Notice that Cells 1 and 2 are approaching a fully charged condition but Cell 3 is lagging behind (C/5 constant current charge illustrated). The system voltage does not indicate a fully charged system. However, any additional charging may damage Cells 1 and eventually Cell 2. Charging should be controlled by individual cell voltages rather than the combined system voltage. This three-cell series connected system shows 11.8V under charge, which one may incorrectly assume to be 3.93V/cell. In reality, the cell voltages range from 3.8V to 4.0V due to cell-to-cell imbalances.

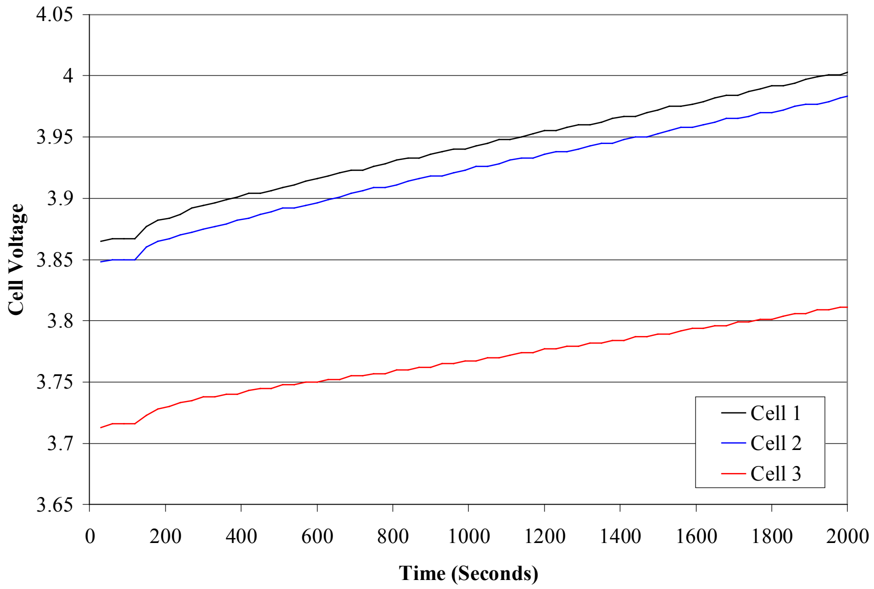

Figure 1: Cell voltages of a series-connected unbalanced lithium battery pack

A variety of methods exist to electronically balance battery pack systems. Discussion of several known methods can be found in published literature [8]. This study utilizes a charge-shunting equalization method shown in Figure 2.

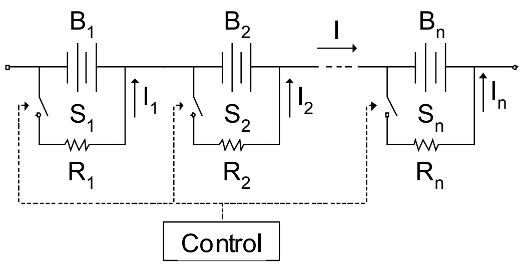

Figure 2: Charge Shunting Balancing Method

This method shunts selected cells with high value resistors to remove excess charge from the highest cells until they match the charge of the lowest cells.

2 Test Configuration

The test hardware used in this study was two EnerDel 65V15 lithium battery packs. The packs under study were constructed with three EnerDel R-Series 4.44 Amp-hour cells in parallel by 18 in series, for a total of 13.3Ah or 875Wh. Maximum pack voltage was 73.8V (4.10V/cell by 18 cells) and minimum voltage of 45.0V (2.50V/cell x 18 cells). Because of the intended application for the 65V15, this study used a minimum voltage of 50.0V (2.77V/cell). The pack included an EnerDel lithium energy controller (LEC), which included the necessary equalization hardware.

The battery packs (serials 61429 and 68989) were run using the load profile shown in Figure 3. The load profile was chosen to represent a C/2 average rate that included 2C pulses. The load profile was continually repeated until either 526Wh (Pack 61429) or 431Wh (Pack 68989) was depleted. These numbers represent the typical energy consumption of the battery's application, and would bring the battery's SOC to approximately 40% (Pack 61429) and 50% (Pack 68989). The battery was then charged at the C/2 rate until the maximum cell voltage was 4.10V. After charging, balancing was restricted to a maximum of one hour. This sequence is considered one full cycle.

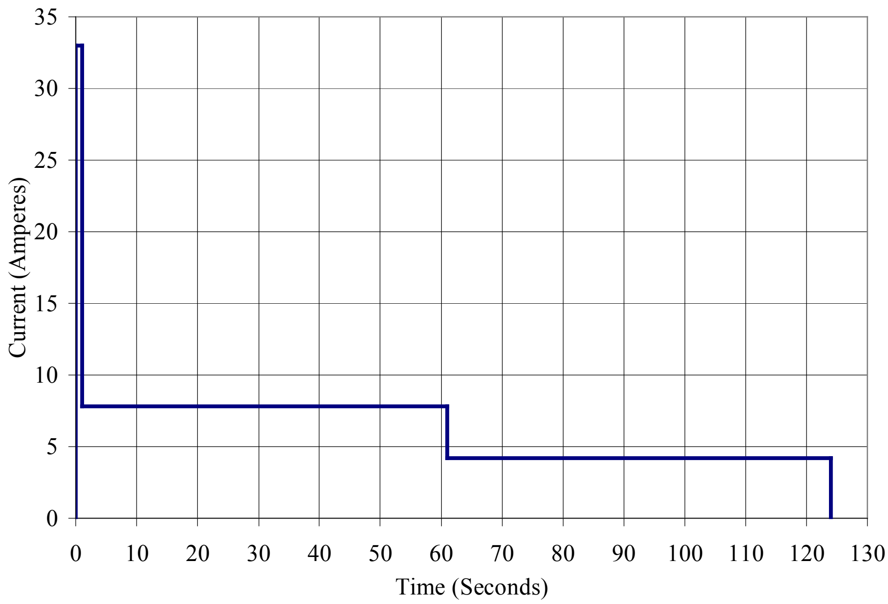

Figure 3: 65V15 Load Profile. Repeated continuously until 526Wh (Pack 61429) or 431Wh (Pack 68989) is depleted.

The electronics were modified to restrict equalization to 1 hour after recharging. The equalization bypass resistors were sized to allow 50mA of equalization current, which is 375 milliamps per Ampere-hour of balancing (50mA / 13.3Ah = 375mA/A). During the 1 hour equalization period, a maximum of 50mAh could be dissipated, which is equivalent to 0.375% SOC.

Every 100 cycles, a reference cycle was performed to benchmark capacity. The reference cycle consisted of a C/5 constant-current discharge to 2.77V/cell (100% depth of discharge) followed by a full charge and unlimited equalization time. The efficiency of the balancing method can be measured by observing the imbalance before and after the reference cycle.

The load profile was applied to the battery using AeroVironment MT-30 battery testing machines. Data for individual cell characteristics and pack performance was collected from the EnerDel LEC via a serial interface. All tests were conducted in a thermally managed chamber at 23°C.

3 Test Results for Pack 68989

Pack 68989 ran for 6491 cycles (Figure 4). This chart represents the capacity as measured by the reference cycles (C/5 performed every 100 cycles). The cumulative discharge on this pack is approximately 2.8 MWh. Cumulative throughput (charge and discharge) is approximately 5.6 MWh. Failure occurred on cycle 6491 when one cell dropped to 2.77V under load:

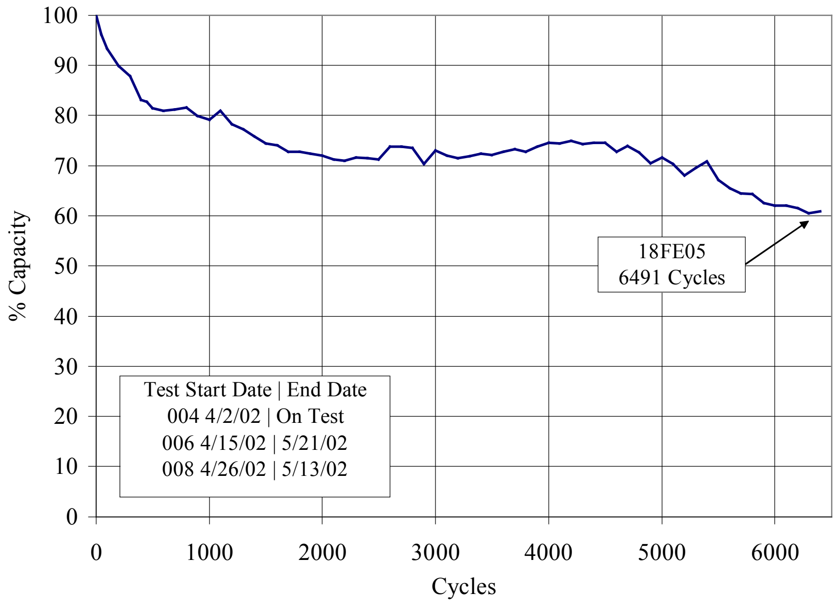

Figure 4: Pack 68989 Cycle life

At the beginning of the cycle, the pack voltage is 73.8V (4.10V/cell by 18 cells). The minimum allowable voltage under cycle is 50.0V (2.77V/cell x 18 cells). Discharge performance can be measured by the midpoint voltage. The midpoint voltage represents the average pack voltage during the discharge, and is calculated by the following equation:

$$V_{Midpoint} = \frac{WattHours}{AmpereHours}$$

It is expected that the midpoint voltage to fall between 73.8V and 50.0V. Refer to Figure 5 for the midpoint voltage during cycles 2000-2400:

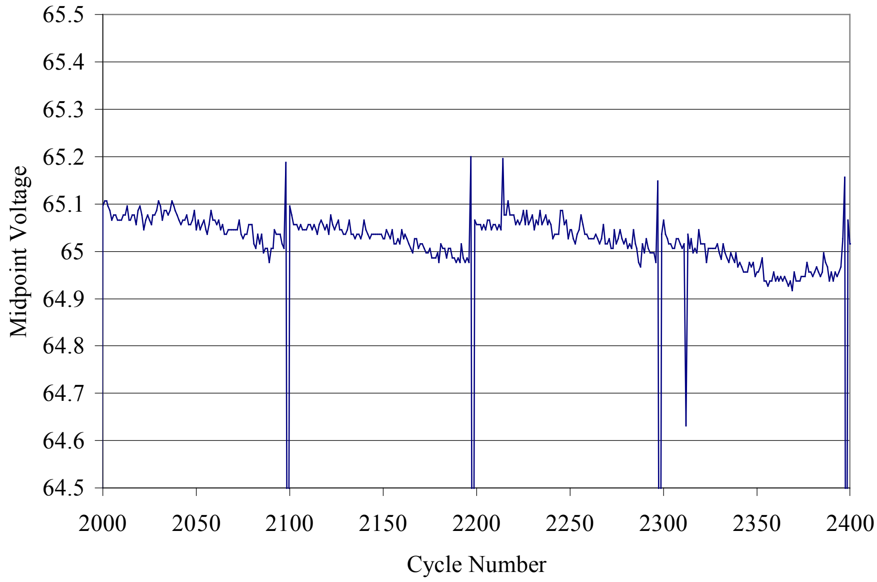

Figure 5: Pack 68989 Midpoint Voltage for cycles 2000-2400

Every 100th cycle, a reference cycle with unlimited equalization time occurs. All other cycles are allowed only 1 hour of equalization time. The effect of limited equalization time can be observed in the midpoint voltage. Immediately after the reference cycle 2100, the midpoint voltage was 65.1V. As the pack cycled through the next 99 cycles with limited equalization action, the midpoint voltage fell below 65V. At cycle 2200, a full equalization cycle took place, and the midpoint voltage rebounded. Figure 5 indicates that approximately 50-100mV of imbalance can take place over 100 cycles if full equalization is not allowed.

The mechanisms contributing to imbalance are not discussed in this paper, however it can be said that age is a contributing factor. Figure 6 is cycles 1000-1400 on the same battery pack:

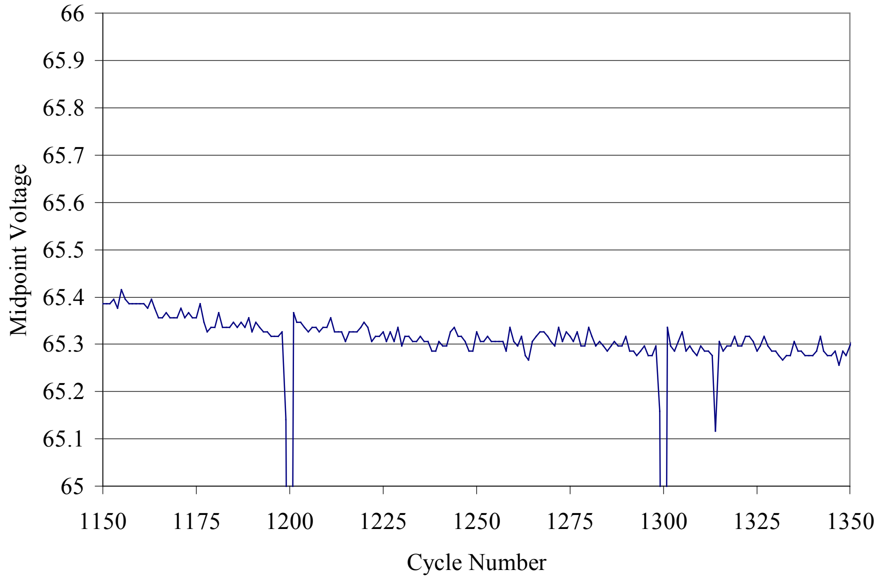

Figure 6: Pack 68989 Midpoint Voltage for cycles 1150-1350

Note that the midpoint voltage is overall higher (65.3V vs. 65.1V shown in Figure 4). This can be attributed to the data was taken when battery pack was newer. Also note that the voltage rebound after the reference cycles (1200 and 1300) is minimal. This indicates that the 1 hour allowed equalization that occurs every cycle is sufficient to keep the pack balanced.

4 Test Results for Pack 61429

Pack 61429 ran for 3370 cycles (Figure 4). This chart represents the capacity as measured by the reference cycles. The cumulative discharge on this pack is approximately 1.8MWh. Cumulative throughput (charge and discharge) is approximately 3.6MWh. Failure occurred on cycle 3370 when one cell dropped to 2.77V under load:

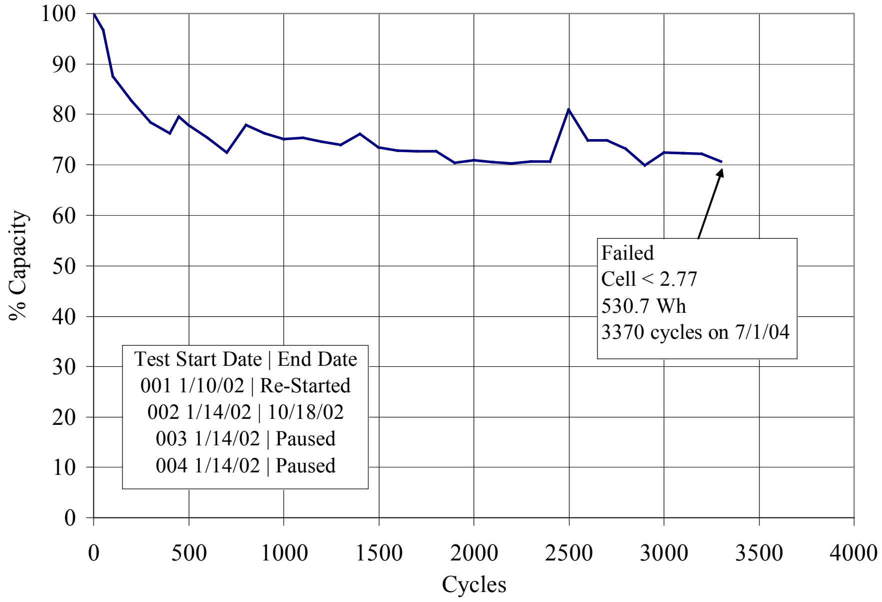

Figure 7: Pack 61429 Cycle Life

Results were similar for Pack 61429. Figure 8 is the midpoint voltage for cycles 2000-2100.

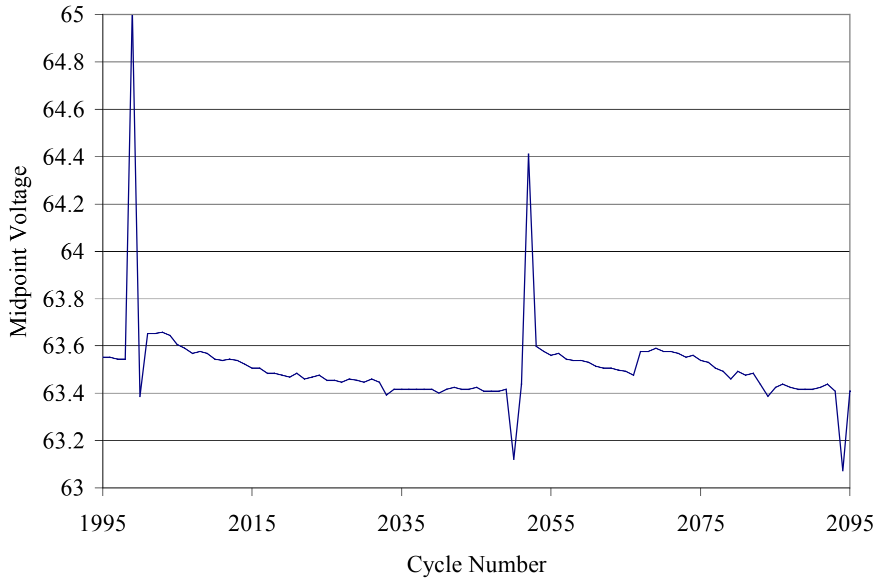

Figure 8: Pack 61429 Midpoint Voltage for cycles 2000-2100

During this interval, an extra reference cycle was inserted at cycle 2050. Notice that the midpoint voltage had dropped to 63.4V at cycle 2049 and rebounded to 63.6V at cycle 2051.

5 Summary

The test hardware used in this study was two EnerDel 65V15 lithium battery packs. The packs were constructed with three EnerDel R-Series 4.44 Amp-hour cells in parallel by 18 in series, for a total of 13.3Ah or 875Wh. Maximum pack voltage was 73.8V (4.10V/cell x 18 cells) and minimum voltage of 45.0V (2.50V/cell x 18 cells). The pack included an EnerDel lithium energy controller (LEC), which included the necessary equalization hardware.

Pack 68989 ran for 6491 cycles, resulting in a cumulative energy throughput of 5.6MWh. Pack 61429 ran for 3370, resulting in a cumulative energy throughput of 3.6MWh. Both packs exhibited similar requirements for cell equalization.

The cell balancing operated at a 375mA/Ah rate for 1 hour between cycles, allowing a maximum of 0.375% SOC balancing per cycle. Every 100 cycles, this restriction was bypassed, and the pack could fully equalize without a time restriction.

Midpoint voltage under discharge was used to quantify battery pack performance. Decreases in the midpoint voltage over consecutive cycles indicated a decrease in performance. Increases indicated an increase in performance. Midpoint voltage was calculated for every cycle.

During early cycles (>1000), the midpoint voltage remained stable during cycling, before and after the reference cycles. This indicated that one hour of equalization at 375mA/Ah was sufficient to maintain pack balance between cycles, and the unlimited reference equalization was unnecessary.

During later cycles (<2000), the midpoint voltage decreased for each subsequent cycle but rebounded from the reference cycles. This indicated that one hour of equalization at 375mA/Ah was not sufficient to maintain pack balance between cycles, and the unlimited reference equalization was necessary.

For battery packs that will have extremely large cumulative energy throughput, this data supports that active equalization is necessary. The balancing rate of 375mA/A used in this study appears to be appropriate for the EnerDel R-Series cell when the cumulative energy throughput is in the MWh range. If more equalization time is allowed per cycle, lower rates could be used.

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Acknowledgements

Greg MacLean, for his depth of knowledge and insight he contributed to this study.
Peter Schneider, for his contributions in the electronic management and equalization hardware.
AeroVironment for the highly capable MT-30 battery testing station.
Delphi Corporation, for creating what is now known as EnerDel Lithium Power Systems.

Author

Stephen W. Moore
Business Development
EnerDel, Inc
8750 Hauge Road
Indianpolis, Indiana 46256
(317) 585-3424
smoore@enerdel.com

Stephen W. Moore is in Business Development for EnerDel, Inc. Stephen began his work with battery pack systems at Texas A&M University, where he had his first journal publication with SAE as an undergraduate student. His master's thesis was focused on computer simulation of lead-acid batteries for hybrid electric vehicles. Stephen participated in and was a faculty member for events such as the Boston Tour de Sol, APS 500, Sunrayce, and the HEV Challenge.

Stephen was hired by Delphi Corporation in 2000 as the Technology Specialist for the Energenix Advanced Development Center. In 2001, he moved to Indianapolis, Indiana, to work with Delphi's Lithium Battery Systems group. In 2002, he became the Systems Engineer for a lithium battery production program. When Delphi and Ener1 formed the joint venture EnerDel, Stephen transitioned to Business Development within EnerDel. His current responsibilities are finding synergies between EnerDel's technology and the marketplace, and then managing those technologies toward production.

EnerDel, Inc
500 W Cypress Creek Rd. Suite 100
Ft. Lauderdale. FL 33309
Phone: 954.556.4020
Fax: 954.556.4031

Fort Lauderdale, FL – October 21, 2004 - Ener1, Inc., (OTC Bulletin Board: ENEI) and Delphi Corp. (NYSE: DPH) have completed a transaction to combine their lithium battery operations into a new company. Ener1 and Delphi expect the new company to benefit from their complementary technical resources, intellectual property and manufacturing assets. The new company will pursue opportunities for high-energy, long-life lithium batteries in diverse markets including power tools, automotive, uninterrupted power supply, medical devices, personal mobility and military applications.

The new company's name, EnerDel, builds upon the venture's capability to deliver new solutions for stored energy and battery power. EnerDel will emphasize the significant performance, size and cost advantages of lithium battery technologies developed by Ener1 and Delphi. Ener1's nanotechnology-based vapor deposition process is expected to offer substantial cost advantages for EnerDel's new battery products due to greater choice of potential electrode materials, faster production times and elimination of binders and coating materials in the production of lithium batteries.