SOLAR CAR TEAMS:

Please note that this paper is being made available because it contains helpful information that is generally applicable to lithium batteries.

Formula Sun is not making the paper available as an endorsement of specific company products that are mentioned in the paper.

Thank you,
FORMULA SUN

Control and Management Strategies for the Delphi High Power Lithium Battery

Stephen W. Moore, Greg MacLean

Abstract

This paper presents an overview of the control and management requirements of high power lithium-based batteries for electric and hybrid electric vehicle systems. Lithium based battery technologies offer performance advantages over traditional battery technologies at the cost of increased monitoring and controls overhead. The additional complexity of the hybrid drive system increases the management burden for accurate state of charge prediction, state of health prediction, cell balancing, and charge management. Delphi has developed a flexible multi-application Lithium Energy Controller (LEC) for the control and management of Lithium Battery Systems (LBS). This paper presents the methodology of design and implementation of the Lithium Energy Controller.

Keywords: Battery management, charge equalization, lithium-ion, state of charge

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. Multi-cell series connected lithium battery systems present a formidable design challenge to create an optimally performing energy storage solution.

Lithium based batteries are intolerant of over-voltage and multi-cell systems require each cell to have an over-voltage detection device. Over-voltage of a lithium based battery can result in cell damage or decreased performance [1-4]. This paper discusses management strategies of lithium based batteries in dynamic environments where recurrent over-voltage is possible, such as in regenerative braking scenarios.

Hybrid vehicle applications present additional challenges for battery management. Batteries must be maintained at a decreased state of charge to reserve headroom for regenerative braking (high charging current) but at a high enough state of charge to provide engine starting power (cold cranking) and launch/torque assist. In addition, batteries must be maintained at a high enough state of charge to compensate for self-discharge over long periods of nonuse.

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 the pack experiencing unbalanced cells. Without controlled artificial balancing, individual cell State of Charge (SOC) will deviate from the average state of charge of the pack. The Lithium Energy Controller (LEC) incorporates balancing electronics that compensates for each cell's unique self discharge characteristic and internal impedance to control each individual cell's state of charge to a desired level. As the cells age with calendar life and cycle life, the LEC maintains records of each cell for state of health status.

2 Lithium-ion Battery Technology

There are a number of lithium based battery chemistries and technologies available to the propulsion and power systems designer, but the problems and risks associated with many of these technologies do not lend themselves to an obvious solution. Two of the most likely candidates for propulsion and power systems are the lithium-ion and lithium polymer technologies. This paper will focus on the less problematic of these, the lithium-ion technology.

Lithium-ion batteries typically consist of a graphite negative electrode or anode, a lithium metal oxide positive electrode or cathode, a microporous separator between the electrodes, and a liquid electrolyte that is comprised of a lithium salt dissolved in an organic solvent. Typical electrolytes consist of $LiPF_6$ salt dissolved in organo-carbonate solvent. The separator does not support ion conductivity itself, but instead allows lithium ions in the electrolyte to move between the electrodes and diffuse into the porous structure of the electrodes. Under charge, the lithium ions move out (de-intercalated) of the cathode's lithium metal oxide and into (intercalated) the anode's graphite. During discharge, the reverse process occurs [8]. Figure 1 illustrates the operation of a lithium-ion battery type.

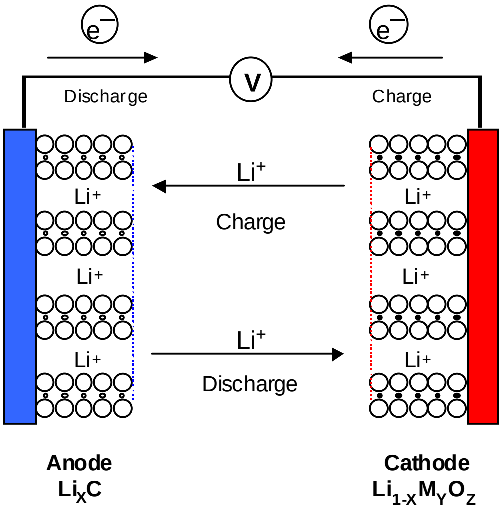


Figure 1: Lithium-ion battery operation

The lithium ions do not normally form metallic lithium under charge or discharge unless the cell experiences abuse. Under normal operating conditions, the electrons move back and forth through the external circuit and the lithium ions move in and out of the structure of the active materials. The lithium ions are electrochemically reduced in the anode's graphite structure. In the cathode's metal oxide structure, the lithium remains in the form of ions.

The cathode metal oxide material experiences a reversible change of oxidation state. Because the cathode material experiences an electrochemical change and not a chemical reaction, there is little opportunity for degradation of the material due to crystallographic reorganization. In addition, the active materials in lithium-ion batteries are insoluble in the organic electrolyte. This eliminates the potential for recrystallization to larger crystal structures that have poor ion diffusivity. Therefore, these cells have the potential for extremely long life and free from the memory effects that are seen in other battery chemistries.

There are three basic assembly methods for lithium-ion cells. The first is the "button" or "coin" cell type. These cells, as the name implies, are small and are constructed with single layers of anode, separator and cathode in a sealed metal case. The second is the spiral-wound type, which typically appears as a cylindrical cell. These cells consist of electrode active materials coated as thin films onto electrically conductive grids or foils, which are tightly wound with a separator around a cylindrical mandrel. The wound electrodes, or "jelly roll", is then packaged into a metal can, which keeps the wind and its materials under compression. If an oval or diamond shaped winding mandrel is used, the "jelly roll" can be flattened and placed in a roughly rectangular metal can. The can often contains safety features such as pressure relief valves or thermal shutoff devices. For additional safety, some cell manufactures also utilize a separator that softens at a particular temperature (i.e. 130-140 ^{o}C), which results in collapse of the pores and shutdown of cell operation due to increased internal resistance.

The third type of lithium-ion cells are of the laminated type, sometimes called Plastic Lithium-ion (PLI) or Bellcore technology [9]. These cells consist of electrodes and separator that are similar to those of the spiral-wound type, except that additional binder material is used in the electrode films in order to facilitate heat-lamination of the layers (figure 2). In this way, compression of the active materials is “laminated” into the cell, thus enabling the construction of large face-area cells without the need for the uniform compression that is provided by a metal can. Cells of this type are usually encased in a multi-layer aluminum foil packaging material and are rectangular in shape. This method of construction also allows for greater flexibility in the cell’s design, with respect to its dimensions, shape, energy and power, as the porosity, material loading, surface area and thickness of the electrodes can be varied to suit the cell’s application needs. In addition to the better heat dissipation properties of a thin rectangular cell, the liquid electrolyte in these cells is contained within the pores of the electrodes and separator, so that no free electrolyte is present. See Table 1 for a performance comparison of laminated lithium-ion and nickel based high power batteries.

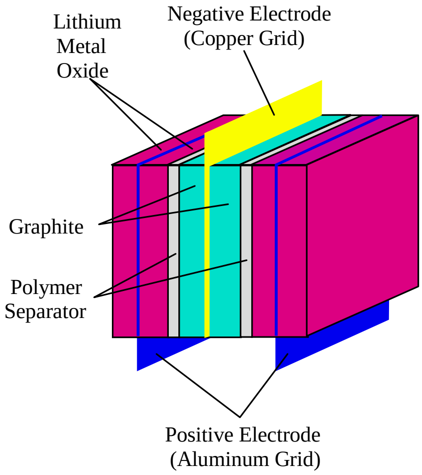

Laminated Bicell Assembly

Figure 2: Laminated Plastic Lithium-ion construction

Table 1: Battery performance comparison

	NiCd[1]	NiMH[2]	Plastic Lithium-Ion[3]
Specific Energy	39 Wh/kg	48 Wh/kg	131 Wh/kg
Energy Density	127 Wh/l	157 Wh/l	244 Wh/l
Specific Power	588 W/kg	1029 W/kg	2610 W/kg
Power Density	1924 W/l	3367 W/l	4854 W/l

[1] “D” size NiCd battery cell, 170g, 52cc, 6.6Wh @ C/5 Rate, 100W @ 100% SOC, 25C
[2] “D” size NiMH battery cell, 170g, 52cc, 8.2Wh @ C/5 Rate, 175W @ 100% SOC, 25C
[3] Delphi LBS cell, 125.5g, 67.5cc, 16.5Wh @ C/5 Rate, 327W @ 100% SOC, 25C

3 Basis of Control and Management

There are several levels of control management goals to consider for a lithium battery system. Listed in order of importance, they are:

3.1 Voltage (State-of-Charge) Limits

The typical organo-carbonate electrolyte solvent used in lithium-ion cells is flammable and subject to electrochemical decomposition. The solvent is technically unstable when subjected to typical cell voltage potentials. When the cell is first charged, the organo-carbonate solvent is reduced on the anode's graphite particles forming a layer of insoluble lithium organic salts and lithium carbonate called the Solid Electrolyte Interface (SEI). Once formed, the SEI layer protects the anode surface from further reduction of the organo-carbonate solvent while allowing lithium ions to pass through it. The SEI layer will grow slowly as it cracks and rebuilds itself as electrolyte seeps through the cracks and reduces at the anode. Cracking of the SEI is caused by volumetric changes of the underlying graphite particles due to intercalation and deintercalation of lithium ions. The continued growth of the SEI layer due to cracking and rebuilding decreases the utilization of the active material and reduces cell performance and life.

Additional problems occur with the organo-carbonate solvent at the cathode electrode during charging. The solvent's instability towards oxidation becomes notable at voltage potentials as low as 4.2 volts, precipitating the generation and accumulation of CO and CO_2 gases after repeated charges. The higher the voltage potential the solvent experiences, the greater the amount of electrolyte decomposition and gas formation. In addition to gas formation at high cell voltages, the electrolyte decomposition produces polymeric byproduct materials that deposit on the cathode active materials. These byproducts pollute the cathode surface and inhibit the active material, reducing cell performance and life.

If the cell's pressure relief valve (spiral-wound type) or the aluminum foil package (laminated type) opens due to excessive internal pressure caused by electrolyte decomposition or high temperature, organic electrolyte vapor will fill the battery enclosure. This vapor within the enclosure may present a safety hazard, depending on the vapor flashpoint and vapor/air mixture.

Control management techniques must be used to avoid high voltage potentials in order to eliminate or reduce the amount of electrolyte decomposition. Keeping the lithium battery at its maximum state-of-charge (i.e. 100% SOC = full charge) may decease its useful life and may cause increased safety risks. Charging a cobalt-based or manganese-based lithium battery to a fraction of its full charge (i.e. 4.0 – 4.1 V/cell and 4.1 – 4.2 V/cell, respectively) may be an effective way to increase the cell's useful life and decrease the safety risk, while at the same time allowing 95% or more of its capacity to be available.

Control management techniques must also prevent lithium batteries from being discharged to excessively low potentials (2.0 – 2.5 V/cell). At these low cell voltages, the copper current collector can dissolve in the electrolyte. The dissolved copper will be plated onto the anode's graphite particles on subsequent recharges of the cell, which will inhibit the utilization of the active material and reduce the cell's performance and life. Repeated excursions to these low voltages can lead to the formation of copper dendrites and shorting of the cell.

3.2 Operating Current Limits

Excessive operating currents can also cause permanent damage to a lithium-ion battery. Under high charging currents, the Li^+ may not diffuse properly into the anode's graphite particles and begin plating onto its surface in the form lithium metal. The plating occurs in such a manner as to form dendritic growth that can puncture the separator and form a conductive short circuit to the cathode. This short circuit is of a "soft" short type, as it only causes a momentary discharge of the cell with a noticeable voltage depression or current spike during charging. Eventually, as the number of these soft shorts increase, the result will be the inability to fully charge the cell.

The plated lithium metal is very reactive toward the electrolyte and will result in electrolyte decomposition at the anode, increasing the SEI layer thickness. This will increase internal resistance and decrease cell performance.

The ability of the lithium ions to diffuse into the anode graphite is dependent on temperature and design. Lithium metal plating at the anode can begin at temperatures of 10 ^{o}C and below, depending on the type of graphite and electrolyte used and the cell's design. At lower temperatures, plating can occur even at normal operating charge currents.

Excessive discharge currents may not permanently damage cells, but polarization will occur. Polarization, due to the inability to move lithium ions through the electrolyte and in and out of the active materials, will greatly reduce the cell's performance.

4 Additional Controls

Lithium-ion battery cells must be controlled so that the predefined limits of voltage and current limits are not exceeded. Careful monitoring and controls must be implemented to avoid any single cell from experiencing over-voltage or over-current due to excessive charging. However, there are additional management controls required for lithium-ion batteries, particularity for series connected cells.

Series connected cells within lithium-ion battery packs pose a challenging control and management problem: each cell in the series string must be individually monitored and controlled. Even though the pack voltage may appear to be within acceptable limits, some cells within the series string may experience damaging voltage due to cell-to-cell imbalances. Notice that Cell 3 shown on figure 3 is at a significantly lower voltage but Cells 1 and 2 are approaching a fully charged condition (C/5 constant current charge illustrated). The system voltage of these series connected cells may not indicate a fully charged system, but any additional charging may damage Cells 1 and eventually Cell 2. Voltage imbalances within a series string can be attributed to differing internal impedances, imbalanced SOC between cells, and thermal gradients within the battery pack. For this reason, it is not feasible to monitor a multi-cell lithium-ion battery pack by 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. In this case, one cell is in jeopardy of being damaged due to high voltage.

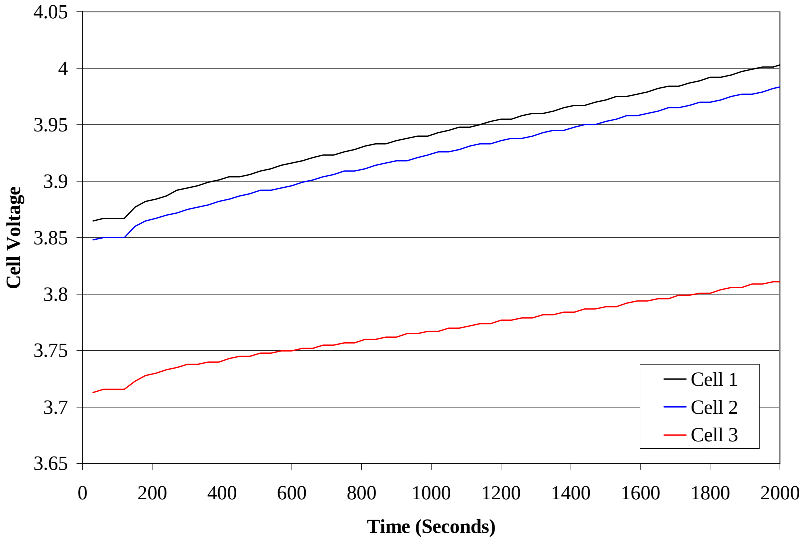


Figure 3: Charge profile of a three series cell unbalanced lithium battery pack

Traditionally, cell-to-cell imbalances in lead-acid batteries have been solved by controlled overcharging. Lead-acid batteries can be brought into overcharge conditions without permanent cell damage, as the excess energy is released by gassing. This gassing mechanism is the natural method for balancing a series string of lead acid battery cells. Other chemistries, such as NiMH, exhibit similar natural cell-to-cell balancing mechanisms.

Because a Lithium battery cannot tolerate overcharging, there is no natural mechanism for cell equalization. Therefore, a controlled artificial equalization method must be employed to negate the effects of any cell-to-cell imbalances within a series string.

Cell balancing is necessary for highly transient lithium battery applications, especially those applications where charging occurs frequently, such as regenerative braking in electric vehicle (EV) or hybrid electric vehicle (HEV) applications. Regenerative braking can cause problems for Lithium-ion battery systems because the instantaneous regenerative braking current inrush can cause battery voltage to increase suddenly. Even when the system voltage appears to be within limits during a current inrush, cell-to-cell imbalances can cause potentially damaging voltage differentials between cells. The charging current from regenerative braking must be controlled by individual cell voltages from within the battery pack, rather than from the system voltage [10].

Thermal gradients within a battery pack system can cause temporary cell-to-cell imbalances. Warmer cells may exhibit lower internal impedance and higher self discharge rates than cooler cells, causing temporarily imbalanced operation. The solution to this problem should not be artificial electronic cell equalization, but proper thermal management. A good thermal management strategy combined with properly placed temperature sensors can minimize the effect of thermally induced imbalances.

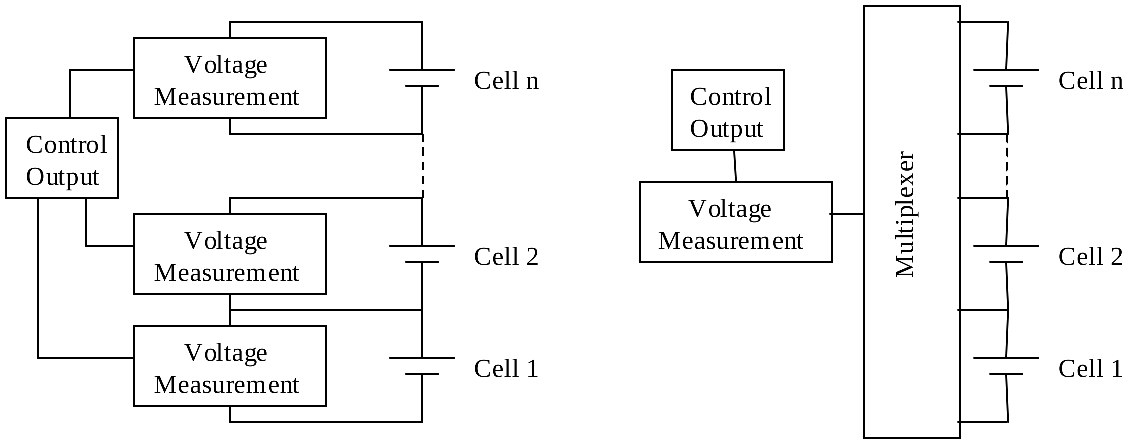
5 Implementation

The Lithium Energy Controller developed by Delphi incorporates three primary control features: individual cell voltage monitoring, battery pack system current monitoring, and electronic cell balancing. These features allow for protection against cell over-voltage (independent of system voltage), protection from over-current events, and optimization of performance by correcting cell-to-cell imbalances. Information from the LEC is communicated over analog and/or digital communications lines to the vehicle controller.

5.1 Voltage Monitoring

Individual cell voltage monitoring is incorporated in the LEC to detect individual cell over-voltage events in a multi-cell series strings. Simple control schemes can be implemented using analog or digital cell voltage sampling to restrict charging current when preset voltage changes or limits are detected (figure 4a). More complex control schemes can be implemented with digital capability, using cell voltages to calculate individual cell charge acceptance, state of charge, and other various parameters.

To reduce cost, a multiplexing architecture can be designed to feature a single analog or digital output by switching the desired cell to the output electronics (figure 4b). Cost saving can be realized by reducing the number of analog control and/or digital sampling circuitry to a minimum. Drawbacks are that only one cell voltage can be monitored at a time. A high speed switching mechanism is required to switch the output line to each cell so that all cells can be monitored sequentially.



(a) (b)

Figure 4: Multi-cell voltage measurement techniques

5.2 Current Monitoring

Series connected battery cells require only a single current monitoring device. Typical current monitoring devices are current shunts (sense resistors) or inductive-magnetic type sensors installed in series with the battery cells.

Current control must be based on cell voltages and temperatures. Discharge current should be limited to the lowest performing cell, controlling discharge current so that any individual cell does not drop below a predefined voltage (typically 2.7 – 3.0 V/cell). Abnormally high voltage drops experienced by an individual cell during discharge are typically caused by high internal impedance or polarization. Low temperatures will result in normally higher internal impedances, so discharge currents should be controlled accordingly.

Charge control should be implemented to restrict charging current to the cell's allowable limits, determined by the cell's design and materials. In addition, charge control must be based on individual cell voltages so that any individual cell does not experience an over-voltage potential. This is illustrated by figure 5. Above 50% SOC, the cell's current should be controlled to avoid an overvoltage potential of 4.1V/cell. Below 50% SOC, the cell has the capability of accepting over a 10C charge rate, but current should be controlled so that the maximum design charge rate of 10C of the cell is not exceeded.

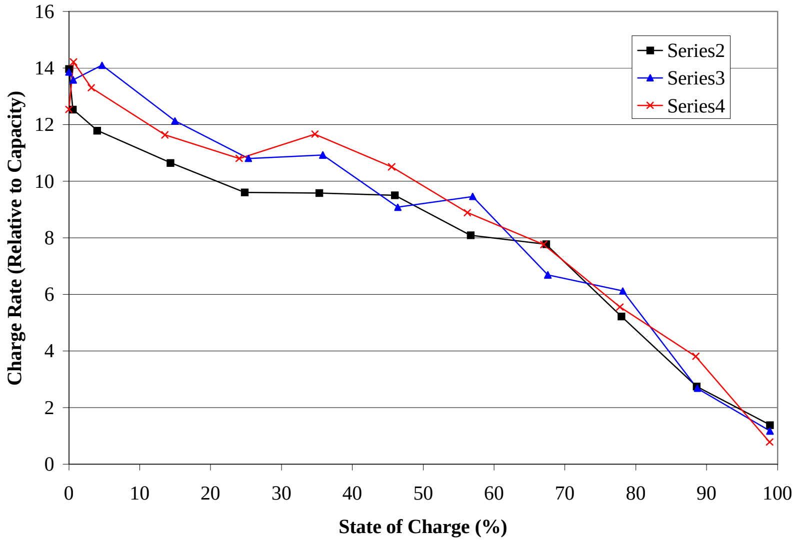


Figure 5: Charge acceptance as a funciton of C.

Age and temperature can effect a cell’s charge acceptance ability, so the charge control should incorporate parameters that adapt the allowable charge current to each individual cell’s ability. Charge current should be limited to the lowest performing cell in the series string.

5.3 Charge Balancing

Charge balancing electronics achieve cell equalization by electronically altering the state of charge of individual cells within the series string. Individual cells may require periodic state of charge adjustments due to drift caused by changes in internal impedance, changes of cell capacity due to aging, increased self-discharge and expose to thermal gradients.

Without cell balancing, charging or regenerative performance of the pack is limited by the highest-charged cell. High power discharges are limited by the lowest-charged cell. Figure 6 illustrates a C/5 discharge of an imbalanced 3 cell series connected battery pack. Notice that the discharge ends prematurely when Cell 3 reaches the predetermined end of discharge condition at 2.8 Volts while the pack voltage is still 8.8 V. Cells within a balanced pack should terminate together at 2.8V/cell, or 8.4 V/pack.

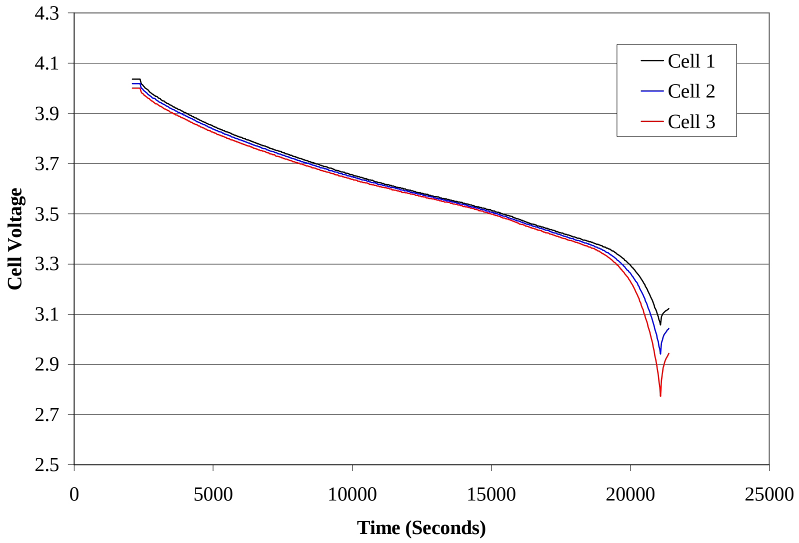


Figure 6: Discharge capability limited by lowest performing cell (Cell 3 in this case)

For energy-based applications, an unbalanced battery will not be fully utilized. Because the charging will be limited to the highest-charged cell, the other cells will not receive a full charge. Therefore, less than 100% of the battery’s capacity will be actually used.

Various methods are available for cell balancing, including current shunts, dissipative methods, switched capacitors, and magnetic/inductive methods. Cell charge balancing is discussed at length in Reference [10] and will not be repeated in this paper. The Delphi Lithium Energy Controller device incorporates a programmable charge-balancing feature that can be optimized for energy or power based applications.

5.4 Thermal Management

This paper primarily discusses electronic management of lithium battery systems, but aspects of thermal management is a critical component of performance optimization. Thermal gradients with a battery pack system can introduce severe differentials of internal impedance, cell aging, and self-discharge rates. Not only should good thermal management be practiced in system design, proper temperature monitoring and electronic control should be implemented to reduce thermal effects on system performance.

6 Summary

Multi-cell lithium-ion battery systems require tightly controlled voltage and current operating conditions. Operating voltage should be restricted to a relatively narrow operating window (2.7-4.1 V/cell) to prevent cell damage. A narrower operating window may be desirable for maximizing battery calendar and cycle life. In addition, lithium-ion cells can be damaged by excessive charging currents. Battery current should be controlled so that the maximum allowable charging current limit is not exceeded while also maintaining the relatively narrow voltage limit window. The maximum allowable charging current is dependent on temperature, so charge current should be controlled accordingly.

Individual battery cells can experience performance degradation due to abuse, aging or exposure to thermal gradients. Degradation can occur in the form of reduced capacity, increased internal impedance or increased self-discharge. These effects may not occur uniformly across all cells within a series string. Since the lithium-ion chemistry does not have a natural cell equalization method to compensate for non-uniform performance within a series string, artificial cell equalization must be implemented.

The Lithium Energy Controller developed by Delphi incorporates the following features for battery level control and systems integration:

- Individual cell voltage monitoring
- Battery pack system current monitoring
- Electronic cell balancing
- State of charge and state of health calculation
- Analog outputs and digital communications

These features allow for protection against cell over-voltage (independent of system voltage), protection from over-current events, and optimization of performance by correcting cell-to-cell imbalances.

7 References

[1] Ph. Blanchard, D. Cesbron, G. Rigobert and G. Sarre, "PERFORMANCE OF SAFT LI-ION BATTERIES FOR ELECTRIC VEHICLES," the 17th International Electric Vehicle Symposium (EVS-17), Montreal, Canada, 2000

[2] M. Okada, H. Yasuda, M. Yamachi, E. Yagasaki, and S. Hashizume, "Porous Polymer Electrolyte Li Ion Battery with Superior Performance," Electric Vehicle Symposium 16 (EVS16), 1999

[3] Segawa, M., S. Hitomi, H. Yasuda, M. Yamachi, "Effects of Porous Polymer Electrolyte on Electrochemical Characteristics for LiNi1-xCoxO2/C System Lithium Ion Cell for Electric Vehicles," the 17th International Electric Vehicle Symposium (EVS-17), Montreal, Canada, 2000

[4] H. Horiba, K. Hironaka, T. Matsumura, T. Kai, M. Koseki and Y. Muranaka, "Manganese Type Lithium Ion Battery for PEV and HEV Use," the 17th International Electric Vehicle Symposium (EVS-17), Montreal, Canada, 2000

[5] Keyser, M., A. Pesaran, M. Mihalic, "Charging Algorithms for Increasing Lead Acid Battery Cycle Life for Electric Vehicles, " the 17th International Electric Vehicle Symposium (EVS-17), Montreal, Canada, 2000

[6] E. Sexton, "Improved Charge Algorithms for Valve Regulated Lead Acid Batteries," IEEE 00TH8490, in *Proceedings of the 15 th Annual Battery Conference on Applications and Advances*, Long Beach, California, January 11-14, 1999, 211-216.

[7] Dennis Corrigan, et al., "Ovonic Nickel-Metal Hydride Electric Vehicle Batteries", the 12th International Electric Vehicle Symposium (EVS-12), Anaheim, CA, Dec., 1994

[8] Ahrens, Daniel W., B. Hanauer, and J. Waters, "Plastic Lithium Ion Energy/Power Systems are Key to Integrated and Affordable Hybrid Automotive Systems," ISATA, 1999, 99CPE003

[9] A. Gordz, et al., "Electrolyte activatable lithium-ion rechargeable battery cell," US Patent and Trademark Office, #5460904, October 24, 1995

[10] Stephen W. Moore and P. Schneider, "A Review of Cell Equalization Methods for Lithium Ion and Lithium Polymer Battery Systems," SAE Publication 2001-01-0959, 2001

8 Authors

Stephen W. Moore
Delphi Automotive Systems, 8750 North Hague Road, Indianapolis, Indiana, 46256, USA
Lithium Battery Systems, Technology Specialist
Phone: 317-579-3854, E-Mail: stephen.w.moore@delphiauto.com

S. Moore graduated with a B.S. and M.S. in electrical engineering from Texas A&M University. He currently is a Ph.D. candidate at the same university.
Since 2000 he has worked as the Advanced Energy Storage Systems Technology Specialist for Delphi Automotive Systems. His current assignment is to the Lithium Battery Systems group as a systems engineer.

9 Photographs

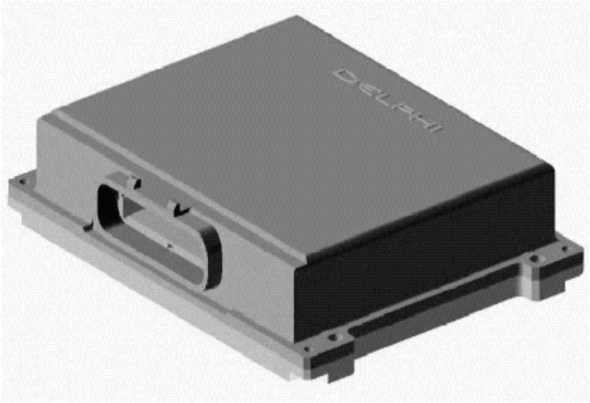


Photo 1: Delphi Lithium Energy Controller (LEC) revision 2