Cell-balancing and State of Charge Algorithms

Analysis of LFEV's project design

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***Abstract*—This research document explores the topic of cell-balancing as a key component to actively monitoring and managing a battery system like the battery pack implemented in the LFEV 2015 senior project. Accurately estimating a cell's state of charge is crucial to the cell-balancing process, and is therefore also researched within the scope of this paper. Suggested improvements are then presented at the conclusion of this research.**

Keywords—cell-balancing; state of charge; algorithm; battery management

I. Introduction

Cell-balancing is important within reference to the Lafayette Formula Electrical Vehicle (LFEV) 2015 project, specifically to the Tractive System Voltage (TSV) team. As the source of the high voltage to the vehicle, the TSV system contains up to four 7-cell battery packs, all of which must be habitually monitored. Voltage and current levels are polled by the Accumulator Management System (AMS) boards and utilized in both a State of Charge (SOC) and cell-balancing algorithm to garner an accurate estimation of the pack's charge at any given time. In an attempt to improve the precision of these previously implemented designs, this paper will explore the different methods of cell-balancing, the significance SOC has on those methods, and hopefully conclude on what alterations can be adopted in future designs of the LFEV.

II. Importance of Cell-balancing

The concept of cell-balancing is a necessary component to any high-voltage battery pack system, as there are multiple factors to be considered for safety purposes. The charge in each cell can vary largely and for numerous reasons such as the change in capacity or internal impedance, but this difference in voltage has the biggest effect on the state of charge of the pack. Having one cell with an outlier voltage level can reach the system's upper or lower threshold at a faster rate than the rest of the cells, and result in an inaccurately charged pack [3].

A. Safety

Within the scope of the LFEV project, a solid cell-balancing method is crucial for the safety of the packs. Due to internal parameters of each cell in a pack, one cell could reach its maximum voltage level before the rest of the cells. Without proper preparation, this could result in a particular cell becoming overcharged, the effect of which is potentially catastrophic and harmful to anyone within reasonable distance of the system.

B. Maintainability

Similarly the lack of such a balancing system will overtime result in the voltage levels of each cell to drift further from each other over each charge and discharge cycle, which inherently decreases the efficiency of the pack. In terms of maintainability, this will greatly affect the degradation of each cell, and in turn shorten the life of the pack as whole, solidifying the need for a system that will ensure it can operate for the foreseeable future [3][6].

III. Methods

A. Active Cell-balancing

Active cell-balancing methods refer to any procedure in which the energy on a highly charged cell is distributed to the cells of lesser charge, therefore 'balancing' the energy of the cell system [2]. One such method is known as capacitave cell-balancing, or charge shuttling, whose naming is indicative of its procedure. In this configuration, a system of switches and capacitors are are used to 'shuttle' or transfer energy back and forth between high and low voltage cells.

A.1 Advantages & Disadvantages

One major advantage of this particular active cell-balancing method is that there is very little control needed to operate the switching between capacitors. However, its disadvantage comes with the length of time to which the cells become equalized. As can be assumed, any increase in the equalization rate of the cells will also increase the complexity of the control system used in the process [2][4]. Although there are numerous derivations of both this method as well as other active implementations using inductors and transformers, the scope of this research will be of greater focus on the methods utilized in the LFEV 2014 team's design: passive cell-balancing.

B. Passive Cell-balancing

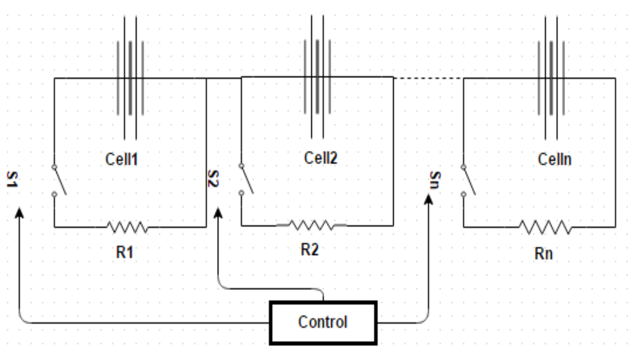

Fig. 1. Resistive Shunt Circuit

This cell-balancing technique involves bypassing or dissipating energy from a highly charged cell until the lesser charged cells come within range to its voltage level. The specific configuration applied in LFEV 2014's design was a controlled shunt resistor, which reduced the current flow to the highly charged cell through the operation of a controller and switches, as depicted in Figure 1 [1].

This system determines which cell to bypass by evaluating the voltage levels polled from the cells, and effectively 'activates' the resistor associated with that particular cell for the necessary number of charging cycles [4]. Specifically, the LFEV 2014 team's control set the state of any given cell to bypass when it came within range of its peak voltage. The cells used within the range of the LFEV project are of the lithium iron phosphate type, and as such the minimum voltage needed to enter the bypass state is 3.585 V, which is slightly below the maximum allowed 3.65 V. This bypassing state forces the cell in question to charge at a rate 0.8x slower than the rest of the cells, allowing the others to “catch up” during the next cycle of charging, and to attempt to keep the cells charge balanced [1].

B.1 Advantages & Disadvantages

The major advantage of this passive cell-balancing method is in its simplicity. Its implementation in the LFEV 2014 design involves only resistors, switches, and low complexity control which makes it a very affordable choice that also provides a fairly fast rate of equalization. One of its most significant disadvantages is in the loss of energy during the equalization process. These losses take form as the heat dissipated from the resistor during bypass state of the system. As a result any pack utilizing this method is most often required to include some form of a thermal management system [2][4].

III. Importance of State of Charge

An important part to note about any cell-balancing method is that the voltage, current, and temperature levels of each cell alone are merely components used to determine both the individual cell and the overall pack's state of charge. By definition the state of charge is the level of available capacity of the battery, most commonly displayed to the system's user as a percentage from 0 to 100, indicating a range from completely dead to fully charged [3] [6]. The accuracy of a system's cell-balancing algorithm is directly dependent on the SOC estimation algorithm, since it operates based on the current

SOC of each cell within the system. As such, increasing the precision of this estimation is crucial in the attempt to approve the LFEV's cell-balancing process.

IV. ALGORITHMS

A. Open Loop Coulomb Counting

One of the most common form of calculation associated with SOC algorithms is coulomb counting, as depicted in Equation 1.

$$SOC_c(t) = SOC_c(0) - (1/Q) \int_0^t I(t)\, dt \quad (1)$$

Here the SOC is estimated using the integration of all of the charge having left the cell through the amount of current that has passed through it [6]. The SOC algorithm used in LFEV 2014's design used the same process, as well as tailoring the limits to correspond with the projects specifications. LiFePO4 cells are extremely sensitive to being charged or discharged to either of their voltage thresholds [6] so to account for this, the team developed a Gain and a Bias constant to adjust their linear interpretation of the SOC (y) and the coulomb count (x) as seen in Eqn 2.

$$y = Gx + B \quad (2)$$

In order to adjust the SOC estimation for any miscalculations, the control implemented in LFEV 2014's design constantly updates the Gain and Bias values using previously calculated SOC readings, as depicted in Equations 3 & 4.

$$Gain = ax(SOC1 – SOC2) \quad (3)$$

$$Bias = a(SOC1 – SOC2) \quad (4)$$

Here 'a' is a predetermined 'learning rate' that can be established by the user of the system. This rate allows the user to choose – based on the configuration of their battery system – how fast they want the SOC estimation to reach the correct values. It may seem plausible to implement it with a high learning rate in an attempt to increase the efficiency of the algorithm, however, too large a rate will cause the estimation to overshoot the desired readings [5].

B. Closed Loop Coulomb Counting

Closed loop coulomb counting is similar to the above described coulomb counting but with a feedback factor to correct any estimation errors. Although the LFEV 2014 team's algorithm for the SOC estimation was an attempt at producing CL coulomb counting, there is a finer tuned estimation algorithm that could be applied to the SOC estimation problem known as the Kalman filter [6].

B.1 Kalman Filter

The Kalman filter is a process used commonly in signal processing, as it estimates and predicts the state of a signal (in this scope – SOC) at a desired point in time. The main equation to represent this algorithm is shown in Equation 5.

$$X_t = K_t Z_t + (1 - K_t)X_{t-1} \quad (5)$$

Here the estimation is determined using Z – the measured value, in addition to the previously predicted estimation. Both parts of the estimation are scaled by a factor of K, referred to as the Kalman gain. This gain could be best compared to the 'learning rate' implemented in the LFEV 2014 algorithm, however the major difference is that K does not remain constant throughout each cycle. Instead the Kalman filter updates this gain throughout every calculation and estimation, in order to produce the optimum scaling factor for each step in time of the system [7].

V. CONCLUSIONS

This paper has laid out the hierarchy of elements and subsystems pertaining to developing an efficient cell-balancing algorithm for a battery pack, specifically LiFePO4 cells, in an attempt to devise an approach to improve the algorithm. While applying an active cell-balancing method may reduce the thermal dependencies that the current design holds, its complexity and cost fall out of the scope of the LFEV project. Because of the role that the SOC estimation plays in any cell-balancing algorithm, any allowable alteration to that specific algorithm could greatly improve the system's operation. To do so, LFEV 2014's work could be extended to fit with the Kalman filter design. Although the calculations of the Kalman gains needed for this implementation are far beyond the typical experience of undergraduate research, doing so would undoubtedly increase the precision of the SOC estimations and subsequently the cell-balancing algorithm as a whole.

VI. References

[1] LFEV 2014, “Cell Balancing Algorithm,” unpublished.

[2] S. W. Moore and P. J. Schneider, “A review of cell equalization methods for Lithium ion and Lithium polymer battery systems,” Society of Automotive Engineers, Inc, 2001.

[3] P. Anderson and O. Collin, “Parameterization of a 14.5 Ah LiFePO4-battery cell,” Chalmers University of Technology, Division of Electrical Engineering, Sweden, 2009.

[4] M. Daowd, N. Omar, P. Van Den Bossche, and J. Van Mierlo, “Passice and active battery balancing comparison based on MATLAB simulation,” unpublished.

[5] LFEV 2014, “State of charge algorithm,” unpublished.

[6] I. Husain, “Electric and hybrid vehicles – design fundamentals,” 2nd edition, CRC Press, 2011, pp 153-286.

[7] G. L. Plett, “Extended Kalman filtering for battery management systems of LiPB-based HEV battery packs: Part 1. Background,” *Journal of Power Sources*, pp 134, 252-261, 2004.