Journal of Power Sources 267 (2014) 603–609

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Performance comparison of active balancing techniques for lithium-ion batteries

Federico Baronti, Roberto Roncella, Roberto Saletti*

Dipartimento di Ingegneria dell'Informazione, University of Pisa, Via G. Caruso 16, 56122 Pisa, Italy

HIGHLIGHTS

- We compare five topologies for balancing series connected lithium-ion batteries.
- We compute the balancing time and energy losses with a simple analytical model.
- Statistical simulations are performed by randomly generating the charge imbalance.
- Equalisation based on charge transfers from cell to cell is the most effective.

ARTICLE INFO

Article history:
Received 30 December 2013
Received in revised form
24 March 2014
Accepted 3 May 2014
Available online 3 June 2014

Keywords:
Battery equalisation
Battery management system
Lithium-ion batteries

ABSTRACT

A simple but effective analysis to calculate the performances achievable by a balancing circuit for series-connected lithium-ion batteries (*i.e.,* the time required to equalise the battery and the energy lost during this process) is described in this paper. Starting from the simple passive technique, in which extra energy is dissipated on a shunt resistor, active techniques, aiming at an efficient energy transfer between battery cells, are investigated. The basic idea is to consider the balancing circuit as a DC/DC converter capable of transferring energy between its input and output with a certain efficiency and speed. As the input and output of the converter can be either a single cell or the entire battery pack, four main active topologies are identified: cell to cell, cell to pack, pack to cell and cell to/from pack (*i.e.,* the combination of the cell to pack and pack to cell topologies when the converter is bidirectional). The different topologies are compared by means of statistical simulations. They clearly show that the cell to cell topology is the quickest and most efficient one. Moreover, the pack to cell topology is the least effective one and surprisingly dissipates more energy than the passive technique, if the converter efficiency is below 50%.

1. Introduction

Charge imbalance is a major issue in large-size lithium-ion batteries, in which several cells are series-connected to meet the voltage requirement of the application [1,2] Differences in cell capacity, self-discharge rate and operating temperature cause the charge level to vary from cell to cell. This lack of uniformity in the charge stored in the cells of the battery reduces its usable capacity and lifetime [3]. Charge equalisation is, thus, an important task performed by the Battery Management System (BMS) to provide a safe and effective use of the battery [4]. Different approaches have been investigated to modify the charge level of each cell in a controlled way, in order to bring all the cells to the same charge level at the end of the balancing process [5–11]. They are usually classified into passive and active circuits [12]. The former are only capable of dissipating a controlled amount of energy from each cell of the battery and usually consist of a shunt resistor and a switch per cell. In addition to the intrinsic inefficiency of the method, the balancing speed is limited by the amount of power that can be dissipated in the BMS. Active circuits are more complex and aim at an efficient and fast energy transfer between the cells. In this way, energy is not wasted but moved among the cells to reach charge equalisation. A thorough survey of the different balancing circuits can be found in [12,13].

Those papers also provide a valuable comparison of the different techniques by assigning a “reasonable” mark to various parameters, such as cost, circuit complexity, speed and efficiency. However, these parameters give only a qualitative indication of the performance offered by each technique in balancing the battery, *i.e.,* the balancing time and the energy losses. In fact, not only do these two

* Corresponding author.
E-mail address: r.saletti@iet.unipi.it (R. Saletti).

http://dx.doi.org/10.1016/j.jpowsour.2014.05.007
0378-7753/

performance figures depend on the balancing circuit parameters, but also on the strategy that is applied to equalise the battery. Therefore, the comparison presented in [12,13] needs to be completed with a deeper and more quantitative analysis.

The objective of this paper is to extend the analysis carried out in [12,13] by developing a generalised model of various balancing circuits, which allows us to derive the optimum balancing strategy for each balancing circuit topology. Optimum balancing means here that battery equalisation is obtained with minimum energy losses. The underlying idea is to represent the balancing circuit as a system capable of transferring energy between its input and output, which are either the cell or the battery terminals. The energy transfer occurs with a certain efficiency and speed, which depend on the circuit implementation, as shown in [13]. As a result, the balancing time and the energy losses of each balancing topology are calculated as a function of the efficiency and speed of the balancing circuit and the initial charge imbalance. Statistical simulations are performed to compare the performance of the different balancing techniques, by generating a large number of random charge imbalances and by evaluating the probability density function (PDF) of the balancing time and energy losses.

This paper is organised as follows. Section 2 describes the generalised model of the different balancing topologies, from which the optimum balancing strategy is derived, as shown in Section 3. Section 4 and 5 describe the comparison methodology and the results of the statistical simulations, respectively. Finally, some conclusions are drawn in Section 6.

2. Modelling of battery equalisation topologies

A generic balancing circuit applied to a battery pack consisting of N cells can be seen as an $(N+1)$-port balancing network. As shown in Fig. 1, N ports (cell ports) are connected to the individual cell's terminals and one (pack port) to the terminals of the battery pack. The implementation of the balancing circuit determines the relationship between the ports' currents, and thus how charge is transferred between the battery cells. The voltage at the cell ports is the voltage of the cells ($V_h, h \in 1 \dots N$), whereas the overall voltage of the battery V_{N+1} is applied to the pack port. The different balancing circuits can be grouped in five topologies: *Cell to Null*, *Cell to Cell*, *Cell to Pack*, *Pack to Cell*, and *Cell to/from Pack*, according to the way by which energy is transferred between the battery cells. Each energy transfer is the result of a DC/DC energy conversion characterised by an energy loss and a transfer time, which depend on the efficiency and output power of the DC/DC converter used in the balancing circuit. The aim of this section is to derive an analytical model for each topology, which allows the computation of the balancing performances that can be achieved.

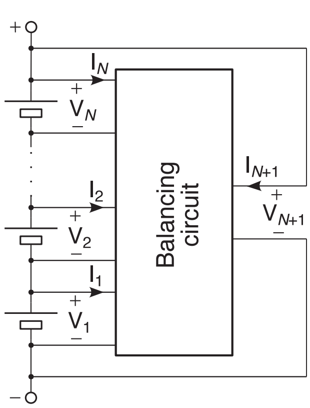

Fig. 1. Model of a generic balancing circuit.

To this end, the port currents $I_j, j \in 1 \dots N+1$ of the balancing network will be related to the parameters of the DC/DC converter and to the control strategy of the balancing circuit, which equalises the battery with minimum loss of energy. We neglect the dynamic behaviour of the battery and the dependence of the cell open circuit voltage OCV on the state-of-charge SoC [14]. In fact, the cell voltage is considered constant and equal to its average value $\overline{V}$ in the SoC range identified by the least and the most charged cells in the pack. This approximation leads to simply modelling the balancing network, as the charge flowing through each port of the network depends only on the DC/DC converter parameters, being the port voltages constant. A simple model allows us to derive analytical expressions for the balancing performances achieved by the different topologies, thus making their quantitative comparison possible. It is important to note that the constant cell voltage approximation is acceptable because the balancing currents are typically much smaller than the cell C-rate, the slope of the OCV–SoC curve is rather low, particularly in some kinds of batteries, and the maximum SoC range in which the assumption must hold is usually small (*e.g.,* below 10%). This last hypothesis is a direct consequence of the availability of a balancing circuit in the BMS. Moreover, we assume that the DC/DC converter operates in constant current mode and with constant efficiency. The five balancing topologies and their models are presented and discussed in the following.

- *Cell to Null* (*C2N*, or passive balancing): Energy is selectively extracted from any cell and dissipated in a shunt resistor, until all the cells reach the same charge level. The balancing network is modelled with N zero-efficiency DC/DC converters, the input of each is a cell port of the balancing network. The currents flowing in the ports of the balancing network are

$$I_j = \begin{cases} I_{\text{sh}}, & \text{if cell } j \text{ is selected} \\ 0 & \text{if cell } j \text{ is deselected or } j = N+1 \end{cases} \tag{1}$$

where I_{sh} is the current through the shunt resistor R. I_{sh} can be considered constant for the assumptions made ($I_{\text{sh}} = \overline{V}/R$). Practical values of I_{sh} are in the order of hundreds of milliamperes and are bounded by the maximum power that can be dissipated in the BMS.

- *Cell to Cell* (*C2C*): Two cells are selected for the energy transfer. Energy is extracted from one cell and delivered to the other. Then, the operation is sequentially repeated on another pair of cells, until all the cells reach the same charge level. The balancing network is modelled with a single DC/DC converter, whose input and output are the ports corresponding to the selected cells. If h and k ($h, k \in 1 \dots N$ and $h \neq k$) are the ports connected to the converter input and output respectively, it follows that

$$I_j = \begin{cases} -I_{\text{bal}}, & j = k \\ \dfrac{I_{\text{bal}} V_k}{\eta V_h} \simeq \dfrac{I_{\text{bal}}}{\eta}, & j = h \\ 0 & j \neq h \text{ and } k \end{cases} \tag{2}$$

where I_{bal} is the constant output current of the converter (usually from hundreds of milliamperes to a few amperes) and η is its efficiency.

- *Cell to Pack* (*C2P*): One cell is selected. Energy is extracted from it and equally delivered to all the cells through the pack's terminals, *i.e.,* the port $N+1$. The balancing network is modelled with