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Short communication

Introduction and application of formation methods based on serial-connected lithium-ion battery cells

Verena Müller[a,*], Rudi Kaiser[a], Silvan Poller[a], Daniel Sauerteig[a], Radu Schwarz[b], Martin Wenger[b], Vincent R.H. Lorentz[b], Martin März[b,c]

[a] Robert Bosch GmbH, Robert-Bosch-Str. 40, 96050, Bamberg, Germany
[b] Fraunhofer Institute for Integrated Systems and Device Technology (IISB), Schottkystraße 10, Erlangen, 91058, Germany
[c] Department of Energy Electronics, Friedrich-Alexander University Erlangen-Nürnberg, 91058, Germany

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ABSTRACT

The process step of formation is one key process to guarantee high performance, long-lasting and safe automotive lithium-ion cells. Since the formation of the cell is the most expensive process in cell manufacturing, reducing process cost and time is advanced. The state-of-the-art formation process includes the cycling of lithium-ion cells each on its own power electronic channel which amounts to about 38% of the total formation costs. Therefore, this paper proposes an optimized formation method by serial-connected lithium-ion cells. Due to small resistance and capacity deviations conditioned by manufacturing tolerances, charge balancing is necessary for formation of serial-connected cells. This paper introduces several serial interconnection circuits for serial cell formation, like passive balancing or drop out system. Furthermore, the associated influences on the formation process parameters, e.g. the charging profile and the charge current control are investigated. The comprehensive comparison of serial formation techniques reveals cost reduction potentials and challenges regarding the process control.

1. Introduction

The formation process is the final process step in manufacturing automotive lithium-ion (Li-ion) cells. The formation process is initiated by filling the liquid electrolyte into the cell. After a certain soaking time the pre-charging sequence with small current to a low state of charge (SOC) marks the first activation of the cell. Pre-charging is followed by several aging intervals at elevated temperatures for homogenous wetting and charge distribution. During the conditioning phase, the cells are charged to SOC 100% with a constant current constant voltage (CCCV) charging protocol and run through aging sequences for self-discharge characterization. Finally, the cells are CCCV charged and discharged several times in order to check the capacity and determine the internal resistance. The key factor for a high performance and long-lasting Li-ion cell is the formation of the solid electrolyte interphase (SEI). Electrolyte decomposition products are formed on the negative electrode surface during the first charge/discharge cycle. Peled [1] first introduced and described the characteristics of the SEI. The most important function of the SEI is the protection against further electrolyte decomposition and graphite exfoliation while being highly permeable for Li-ions [2–6]. Even though the SEI is mainly formed during first cycling, it grows continuously over lifetime [7,8] and due to crack formation caused by particle expansion [9–12]. This leads to loss of cyclable lithium and enables graphite exfoliation. As reported in literature, the cell aging behavior is mainly influenced by the initial SEI formation and its growth over lifetime [8,13]. In addition to the influence on SEI quality, the formation process is also the most expensive process step in cell production with a share of 18 to 32% [14–16]. Wood et al. revealed that the cell formation causes about 6.4% of total automotive Li-ion pack costs [17].

In order to reduce formation process costs, this paper introduces the formation of serial-connected Li-ion cells. Due to production tolerances, e.g. of the coating thickness of the electrodes, there are deviations in capacity and impedance which demand charge balancing between serial-connected cells [18–21]. The cost reduction potential of these serial formation charge balancing methods is shown as well as their influence on the

* Corresponding author.
E-mail address: verenamueller-D@gmx.de (V. Müller).

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formation procedures. Therefore, the requirements for serial formation are derived and an overview of different interconnection circuits is given. Subsequently, the impact of the most promising balancing methods on the formation process and the charge profile is compared to serial charging without charge balancing.

2. Overview of serial formation methods

2.1. Evaluation criteria for a serial formation interconnection circuit

The requirements on the serial formation system split into process and product related demands. Regarding the process, cost optimization is one key requirement. Hence, the cost optimization potential for serial formation methods is assumed based on researches of state-of-the-art Li-ion cell production. A baseline cost calculation for a state-of-the-art formation process can be up scaled by using literature values [22,16] and a cell production volume of 12 million cells per year. The process costs are mainly separated into investment costs for the power electronics (PE), the costs for trays in which the cells are fixed and carried through the process and other costs e.g. facilities and labor. An overview of this baseline cost calculation is given in Fig. 1. The PE invest devides into cost for the PE channel, the electrical contacting of the cell, the temperature and voltage measurement unit and in the case of serial formation an additional charge balancing electronic. However, the PE channels amount to the highest costs and, therefore, the largest cost reduction potential. A comparison of investment costs for a standard PE channel (5 V maximum voltage, single cell formation) with a high voltage PE channel (60 V maximum voltage, serial cell formation of up to 14 cells) reveals a cost reduction potential of up to 48.5% of the initial total PE invest. As the voltage and temperature of every single cell must still be monitored, no further reduction can be achieved regarding these components. For the drop out system which is described later, also the necessity of single cell power line contacting remains. The costs for the additional charge balancing circuit are calculated based on the drop out system. For the implementation, at least two electrical switches per cell are needed. If MOSFETs are applied, four MOSFETs per cell are necessary to enable charging and discharging. Since the full charging/discharging current must be bypassed, higher costs for the conductive tracks, contacts and switches are expected. However, the development of the hardware for the drop out electronic (Fig. 2b) and a cost extrapolation for the designed circuit board for a production of 12 Mio. cells per year showed an increase of 2.5% of the initial 60 V PE investment cost. In total, a cost reduction potential of 46% of the PE investment costs (including balancing circuits) can be achieved. This leads to a total cost reduction potential of up to 17.5% of the total single cell formation costs.

Another process influencing evaluation criteria is the electrical efficiency of the system which affects the energy demand. Furthermore, the complexity of the circuit must be considered.

Product related demands include the influence of the serial formation methods on the formation protocol. Some systems may cause changes in the charging profile of the cells, e.g. a pulsed charge current. The common CCCV charge regime for single cell formation is not applicable due to serial connection. Other concepts may prohibit an exact charge current control of individual cells, leading to an uncontrolled charge amount per cell. This impedes the capacity determination which is an important quality criteria for Li-ion cell production. If the cells are charged in series without any charge balancing system, reaching an equivalent cut-off voltage of all cells is not possible. The charging needs to be terminated as soon as the first cell reaches its maximum voltage to prevent irreversible degradation of the materials. The remaining cells will not be completely charged. Based on experimental researches and comparison of data derived from serial cells we assume a maximum capacity deviation window of 3% for the following elaboration.

2.2. Definition and evaluation of possible interconnection methods

2.2.1. Serial formation without charge balancing

The serial formation of Li-ion cells with no additional charge balancing system is considered as reference system for our work. Consequently, this system promises the highest cost reduction potential, no complexity and high electrical efficiency.

2.2.2. Parallel charging circuit

The parallel charging circuit for every single cell enables to reach the cut-off voltage and also CV charging [19,23]. The cells are connected in series. Additional switches in series and parallel to each cell enable to contact all cells in parallel, if one cell reaches its cut off voltage. Subsequently the parallel connected cells are CV charged until the current comes below a certain limit. Apart from the moderate costs and the good electrical efficiency due to less electrical losses, the system has one major disadvantage regarding the formation criteria. The charging current in the parallel circuit splits depending on the impedances of the cells which are slightly variable. The charging current of a single cell depends on the impedance of the cells. This causes a less controlled formation process.

2.2.3. Active balancing

In contrast to the parallel charging topology described above, active balancing methods rely on charge transfer between cells. A closer look at various implementations reveals that there are

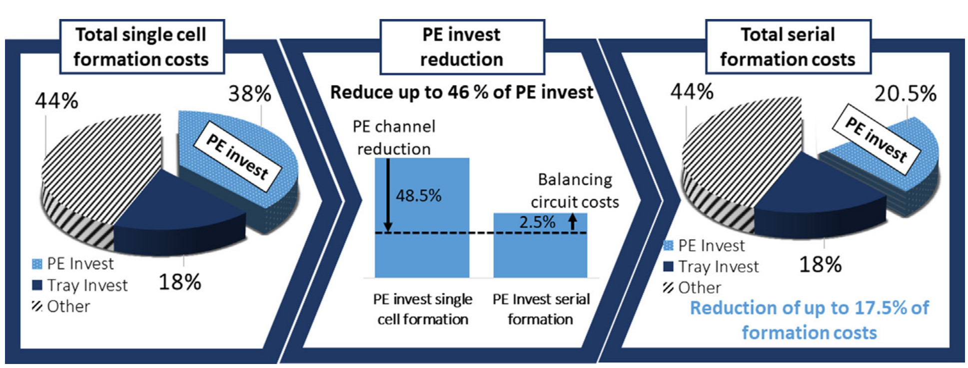

Fig. 1. Formation process cost reduction with proposed serial formation method.