EVERLASTING

Electric Vehicle Enhanced Range, Lifetime And Safety Through INGenious battery management

D8.10 – White Paper 07

February 2019

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 713771

Public

PROJECT SHEET	
Project Acronym	**EVERLASTING**
Project Full Title	Electric Vehicle Enhanced Range, Lifetime And Safety Through INGenious battery management
Grant Agreement	**713771**
Call Identifier	H2020-GV8-2015
Topic	GV-8-2015: Electric vehicles' enhanced performance and integration into the transport system and the grid
Type of Action	Research and Innovation action
Project Duration	48 months (01/09/2016 – 31/08/2020)
Coordinator	VLAAMSE INSTELLING VOOR TECHNOLOGISCH ONDERZOEK NV (BE) - *VITO*
Consortium Partners	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES (FR) - *CEA* SIEMENS INDUSTRY SOFTWARE SAS (FR) - *Siemens PLM* TECHNISCHE UNIVERSITAET MUENCHEN (DE) - *TUM* TUV SUD BATTERY TESTING GMBH (DE) - *TUV SUD* ALGOLION LTD (IL) - *ALGOLION LTD* RHEINISCH-WESTFAELISCHE TECHNISCHE HOCHSCHULE AACHEN (DE) - *RWTH AACHEN* LION SMART GMBH (DE) - *LION SMART* TECHNISCHE UNIVERSITEIT EINDHOVEN (NL) - *TU/E* VOLTIA AS (SK) - *VOLTIA* VDL ENABLING TRANSPORT SOLUTIONS (NL) – *VDL ETS*
Website	www.everlasting-project.eu

DELIVERABLE SHEET	
Title	**D8.10 – White Paper 07**
Related WP	WP8 (Dissemination)
Lead Beneficiary	VITO
Author(s)	Ilya Zilberman (TUM)
Reviewer(s)	Niles Fleischer (ALGOLiON) Didier Buzon (CEA) Daniel Folgmann (LION Smart) Dominik Jöst (RWTH Aachen) Matthieu Ponchant (Siemens) Tijs Donckers (TU/e) Alexander Stadler (TÜV SÜD) Anouk Hol (VDL ETS) Klaas De Craemer / Peter Coenen (VITO) Mario Paroha (VOLTIA)
Type	Report
Dissemination level	PUBLIC
Due Date	M30
Submission date	February 28, 2019
Status and Version	Final, version 1.0

REVISION HISTORY

Version	Date	Author/Reviewer	Notes
V0.1	18/02/2019	Ilya Zilberman (TUM)	First draft
V0.2	27/02/2019	All partners	Peer Review
V0.3	28/02/2019	Carlo Mol (VITO)	Quality check
V1.0	28/02/2019	Carlo Mol (VITO) Coordinator	Submission to the EC

DISCLAIMER

ACKNOWLEDGEMENT

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 713771

TABLE OF CONTENTS

LIST OF ABBREVIATIONS AND ACRONYMS

ACRONYM	DEFINITION
BMS	battery management system
ECM	equivalent circuit model
OCV	open-circuit voltage

LIST OF FIGURES

1 WHITE PAPER: INTRODUCTION

The EVERLASTING project (http://everlasting-project.eu/) will develop innovative technologies to improve the reliability, lifetime and safety of lithium-ion batteries by designing more accurate and standardized battery monitoring and management systems. This allows predicting the battery behavior in all circumstances and over its full lifetime, and enables pro-active and effective management of the battery. This leads to more reliability and safety by preventing issues rather than mitigating them. To raise the awareness of the vital and positive role of battery management systems (BMS), a three-monthly white paper will be written on different BMS topics, aimed at a general technical public. These white papers are a few pages long and will be distributed via the EVERLASTING website and through the partners.

This white paper addresses the topic of cell balancing, especially how balancing strategies can be evaluated regarding their specified goal. First, the actual need for cell balancing is discussed. Subsequently, different balancing goals are defined, depending on the energy storage application. Finally, a balancing strategy is derived, which is suitable for most applications.

2 WHITE PAPER 07: EVALUATION OF CELL BALANCING

2.1 ROOTS OF CELL IMBALANCE

Rising trend for decentralized energy infrastructure, as well as the increasing demand for environmental friendly mobility, require reliable and economical solutions for electrical energy storage. Lithium-ion technology has shown a high potential to fulfill these needs due to its high energy density. However, such applications as electrical vehicles (EVs) require not only high energy density, but also high overall energy content. Due to this fact, battery packs consist of up to 1000 of cells, which are connected in series and in parallel. The desired battery pack voltage, which is linked to tolerable losses and power electronics design, usually determines the number of in series connected cells. The number of parallel cells on the other hand is given by the energy and power requirement of the overall battery system.

Cell's characteristics slightly vary due to manufacturing tolerances, such as variations in the electrode thickness and the overall component connectivity. Because of the limited manufacturing accuracy, even cells from the same batch vary in their initial capacity and impedance. These parameter deviations exhibit a Gaussian distribution and have been already discussed in the literature [1-2][7]. Different cell capacities and impedances imply that within in series connection, there is always a cell or cell block, which reaches its end-of-charge or end-of-discharge voltage first. Due to safety hazards those limits cannot be exceeded, which makes the capacity of the remaining cells unavailable. Further, different self-discharge and degradation rates, due to intrinsic cell parameter variations or presence of temperature gradients, support a drifting apart of cell voltages. Such cell voltage drift results in further premature capacity limitation of the battery pack. In order to avoid possible capacity limitations, balancing circuits are deployed in battery systems.

Generally speaking, cell imbalance is linked to the quality of the cells, which includes initial cell parameter variance and also aging behavior under the same conditions, and system quality, which especially includes thermal management. In case of identical cells and absence of any thermal gradients within the battery pack, there would be no imbalance.

2.2 GOAL OF CELL BALANCING

The goal of cell balancing depends on the application of the battery pack. Whereas an EV aims to reach the maximum possible driving distance, a stationary battery pack, which participates in primary grid control, has to provide required power at any time.

In order to maximize the energy content of the battery pack, the energy of each cell has to be utilized completely. In case of a complete discharge, it means that each cell, starting at 100 % state of charge (SOC) has to reach 0 % SOC, despite the capacity and impedance differences. In case of primary control, on the other hand, the weakest cell or cell block has constantly be at a SOC, which allows required positive or negative current pulse for specified amount of time. However, such applications are rather rare. Maximization of energy content is therefore more suitable goal for cell balancing for most of energy storage applications.

2.3 EVALUATION OF BALANCING ALGORITHMS

In the following practical aspects of cell balancing algorithms are discussed, which all have the same overall goal of energy maximization. In case of imbalance, not all cell capacities are completely utilized and remaining energy has to be redistributed via balancing circuits. A balancing circuit is usually a device, which allows an adjustment of energy level of a single cell or cell block. In general, there are two types of balancing systems: dissipative and non-dissipative. Non-dissipative balancing systems are able to transfer energy without major losses from one cell or cell block to another. An overview of possible implementations was already given in the previous white paper. Almost all non-dissipative balancing systems require a high amount of power electronics such as coils, capacitors and MOSFETs and corresponding control schemes. This fact implies extra weight and cost for battery systems. Therefore, the use of non-dissipative balancing systems is rather uncommon in commercial applications. Dissipative systems are usually favored due to their simplicity and cost advantages. In contrast to energy redistribution, dissipative systems adjust energy levels of single cells or cell blocks by discharging them. Dissipative balancing systems are implemented with a resistor and an electrical switch in parallel to a cell. Since alternative strategies for non-dissipative balancing circuits were already discussed in the previous white paper, in the following practical evaluation of common dissipative balancing techniques is presented.

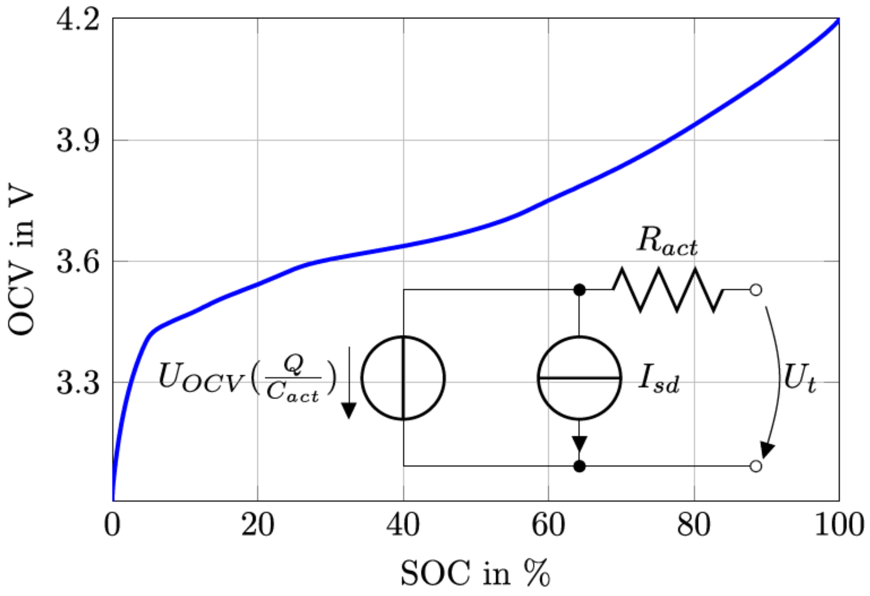

Figure 1: OCV of a NMC/Graphite cell and equivalent circuit model

In general, there are three types of balancing algorithms: SOC based, model based and voltage based balancing. It stands to reason that SOC based balancing is the most accurate one, since it theoretically utilizes the whole charge by definition. However, the actual benefit strongly depends on the accuracy of the SOC determination. SOC is a state, which cannot be directly measured, therefore SOC determination methods, including estimation techniques (Kalman Filters, Neural Networks, etc.) and Coulomb counting are usually applied [3]. Even, if such methods are able to provide accurate results at the beginning of battery life, during the operation, the accuracy quickly decreases and estimation errors often exceed 2-3%. State of the art lithium-ion cells show relative parameter variances far below 1% [6], which makes the use of inaccurate SOC values as input parameter for balancing, inadequate.

One significant property of lithium-ion cells is the non-linear relation between the SOC and the open circuit voltage (OCV), as exemplarily shown in Figure 1. The OCV increases with an increasing SOC. This relationship is given by the potentials of the anode and cathode materials. Under current loads, lithium-ion cells exhibit internal over-potentials caused by the ohmic resistance, mass transport and double-layer effects [4], summarized in the resistance R_{act}. Therefore, measured terminal voltage does not directly reflect the actual SOC. Model based balancing utilizes cell models in order to estimate the cell's over-potential. In that way, it is possible to perform SOC balancing using terminal voltage under load. However, model based balancing algorithms suffer from the same disadvantages as SOC based balancing. The non-linear nature of lithium-ion cells makes it very difficult to implement robust and accurate models, since all model parameters vary over the SOC range, different temperatures and especially during the lifetime.

The most applicable algorithm is the voltage based balancing, since each battery system monitors cell block voltages. The adjustment of cell voltages during the charge seems to be the right choice, since such applications as EV benefit especially from the maximized discharge energy. However, as already stated before, terminal voltage does not necessarily reflect the SOC and therefore voltage balancing under load might deteriorate the imbalance in the battery pack even further. This imbalance depends on the actual charging current, the over-potentials within the cell and the slope of the OCV. Reducing the current might mitigate this problem and therefore constant voltage (CV) phase seems to be suitable for voltage based balancing. However, since the end-of-charge voltage of the limiting cell is usually an input for current control of the charger, the voltage cannot be distorted. Therefore, voltage balancing during the CV phase is also not recommended.

Due to high quality of state of the art lithium-ion cells, intrinsic cell parameter variations are rather low. Additionally, temperature gradients within the pack can be mitigated by specific design measures. This all leads to small voltage drift, which however, cannot be eliminated. Optimal balancing strategy for such battery systems is seldom voltage balancing during long resting phases after previous charge to end-of-charge voltage. After the resting phase most of cell over-potentials are decayed and terminal voltage reflects the SOC of the cell. A discharge of all cells to the minimal voltage in the battery pack dissipated a small part of the discharge energy. As long as such voltage balancing is performed not often it is considered being acceptable.

2.4 CONCLUSION

Due to manufacturing tolerances, lithium-ion cells exhibit variations in capacity, impedance and self-discharge rates, which leads to a voltage drift in battery packs. This voltage drift limits the accessible discharge energy and might be further deteriorated in the presence of temperature gradients. In order to maximize energy content of the battery pack, usually dissipative balancing circuits with bypass resistors are used.

It is recommended to apply voltage balancing during resting periods after full charge of the battery pack. During this process, all cell voltages are adjusted to the minimal cell voltage within in series connection.

2.5 REFERENCES

[1] S. Paul, C. Diegelmann, H. Kabza, and W. Tillmetz, “Analysis of ageing inhomogeneities in lithium-ion battery systems,” *Journal of Power Sources*, vol. 239, pp. 642–650, 2013.
[2] S. F. Schuster, M. J. Brand, P. Berg, M. Gleissenberger, and A. Jossen, “Lithium-ion cell-to-cell variation during battery electric vehicle operation,” *Journal of Power Sources*, vol. 297, pp. 242–251, 2015.
[3] W. Waag, C. Fleischer, and D. U. Sauer, “Critical review of the methods for monitoring of lithium-ion batteries in electric and hybrid vehicles,” *Journal of Power Sources*, vol. 258, pp. 321–339, 2014.
[4] A. Jossen, “Fundamentals of battery dynamics,” *Journal of Power Sources*, vol. 154, no. 2, pp. 530–538, 2006.
[5] C. Campestrini, T. Heil, S. Kosch, and A. Jossen, “A comparative study and review of different Kalman filters by applying an enhanced validation method,” *Journal of Energy Storage*, vol. 8, pp. 142–159, 2016.
[6] C. Campestrini, P. Keil, S. F. Schuster, and A. Jossen, “Ageing of lithium-ion battery modules with dissipative balancing compared with single-cell ageing,” *Journal of Energy Storage*, vol. 6, pp. 142–152, 2016.
[7] M. Dubarry, N. Vuillaume, and B. Y. Liaw, “Origins and accommodation of cell variations in Li-ion battery pack modeling,” *Int. J. Energy Res.*, vol. 34, no. 2, pp. 216–231, 2010.