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

D8.9 – White Paper 06

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

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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 behaviour 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.

In this white paper we address a topic that is often given too little attention, when discussing balancing. Most scientific papers on this topic deal with different electrical schemes to maximize the balancing current. However, another important aspect of balancing is deciding which current to apply to which cell: this is the so-called balancing strategy. We will explain that the balancing strategy is equally important as the electrical setup and smart combinations of both lead to the optimal balancing solution. To get there, this paper is divided into three chapters. The first one discusses the reason for balancing. The second chapter then gives an overview of possible active balancing circuits and is followed by the third chapter, which presents possible balancing strategies for the different circuits.

2 White Paper 06: Balancing - What vs How

2.1 Reasons for Balancing

Before discussing a balancing strategy, it is important to understand the reasons why balancing is necessary in the first place. Therefore, this chapter recapitulates the reasons for and effects of balancing. The battery packs of stationary energy storage applications or electric vehicles, like a Tesla Model 3, require batteries consisting of several thousand single cells. The array of the cells in series and parallel connection is determined by the application. Normally the nominal voltage of the power electronics defines the number of serial connected cells. The overall power and energy demand of the application and the electrical characteristics of the applied cell conditions the parallel-connected cells. Different cell formats offer different advantages. An application with large format cells is easier to assemble and need less monitoring effort than the same application with small format cells. The advantages of small format cells compared to large format cells are flexibility, safety and reliability. Independently of the cell format, the ageing behaviour of the battery pack is usually derived from a single cell, like it is shown in References [1–3].

In reality a cell's characteristics slightly vary due to manufacturing tolerances, like variations in the electrode thickness and the overall component connectivity. As a consequence of the limited manufacturing accuracy, even cells from the same batch vary in their initial capacity and impedance. These parameter deviations show a Gaussian distribution and have been observed in several studies [4–6]. In addition, Baumhofer *et al.* showed that cyclic ageing increases the cell parameter variance compared to the initial distribution. This even occurred under the same ageing conditions. [7]

Because of this cell-to-cell deviations cell voltage monitoring in a battery pack is a vital task. Especially keeping a cell's voltage within the end-of-charge and end-of-discharge limits is crucial to prevent safety hazards and premature cell degradation. Due to the parameter variation, one cell-block within the serial string of the battery reaches these limits earlier than the others. When discharged, usually the cell-block with the least capacity and/or the highest impedance reaches the end-of-discharge criteria first, assumed each cell-block is fully charged at the start of the discharge process. Consequently unused capacity remains within the remaining cell-blocks of the battery. When charged again, a similar problem occurs. One cell-block in the string will reach the end-of-charge criteria before the others and leave them in a not fully charged state. Hence, the serial connection is the reason for the reduced capacity of the battery [8, 9]. Besides the already mentioned intrinsic factors capacity and impedance variation, deviations in the self-discharge rate influence the spread of cell-block voltages. With growing voltage deviations between the cell-blocks in the serial string of the battery, the extractable capacity is further limited, which ultimately shortens the lifetime of the battery compared to a single cell. Extrinsic factors, like a usually occurring temperature gradient between cells due to insufficient cooling, enforce the different power and capacity fades of cell-blocks and further limit the battery capacity [4, 10]. Balancing systems are usually used to increase the available capacity by influencing the cell voltages. Depending on the balancing system either the end-of-charge limit or both the end-of-charge and the end-of-discharge voltage for each cell block is reached during the operation [11]. Due to the adjusted voltage levels, the accessible capacity and the lifetime of the battery can be increased as well.

2.2 Overview of Balancing Circuits

Now that the reasons for balancing are known, an overview of possible active balancing circuits is presented to even out the inhomogeneities between cell-blocks. There are many different ways to realize cell balancing as several review papers show [11–13]. In general, balancing circuits can be divided into active and passive circuits. The feature of passive balancing circuits is the absence of any switches to control the circuit. Therefore, they are not applicable for balancing strategies, since the balancing load cannot be influenced. Active balancing circuits on the other hand allow influencing the balancing process by actively enabling or disabling the balancing process. Figure 1 categorizes and summarizes the most common active balancing circuits. There are five major categories distinguished by the way the load can be redistributed. Beneath the categories an excerpt of common implementations is listed. Each implementation is marked according to the following three characteristics:

- *Non-dissipative solutions* try to redistribute charges within the battery to equalize imbalances in a battery with a minimum of energy losses. In contrast, dissipative solutions convert excess energy into heat, which is no longer available to the system. In this overview only the bypass resistor and the bypass transistor are dissipative balancing circuits.
- *Bidirectional solutions* are capable of transferring energy to the cell as well out of the cell to achieve a balanced battery. A requirement for this characteristic is a non-dissipative solution. The advantage of bidirectional solutions is an extra degree of freedom: the balancing current direction. This allows increasing or decreasing the load of cells.
- *Cell-individual solutions* consider all implementations, which allow controlling the balancing process independently and individually for each cell. This feature offers the most flexibility, since individual cells can be charged and others can be discharged at the same time.

A detailed description of all implementations for each active balancing method is given in Ref. [11]. As this overview shows, there are multiple possibilities to influence the load distribution in a battery. The next step is to come up with a strategy for redistributing the load current through the balancing circuit.

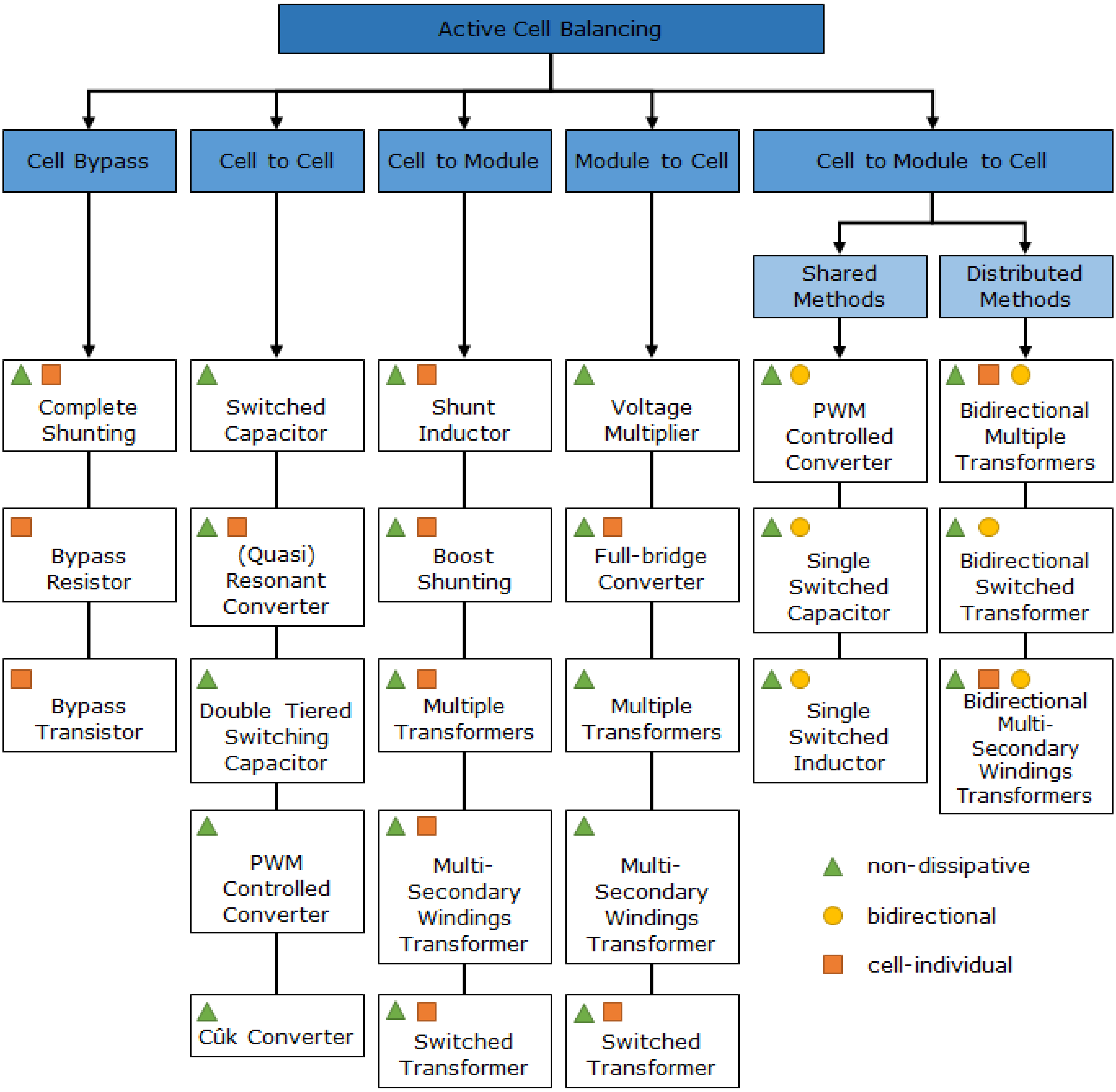

Figure 1: Classification of active balancing methods (adapted from [11])

2.3 Balancing Strategy

As shown in the introduction, an optimal balancing strategy should aim for two goals. The first goal is to maximize the usable capacity. The second goal is to guarantee a homogeneous and minimized ageing of the battery. To maximize the usable capacity, the balancing strategy should guarantee that each cell in the battery reaches the end-of-charge, respectively the end-of-discharge criteria at the same time. To avoid accelerated and inhomogeneous ageing, the balancing strategy should reduce the temperature gradient between cells. If and how these two goals can be achieved in combination with which balancing circuit and strategy, will be discussed in this chapter.

2.3.1 Strategies for Dissipative Balancing circuits

Dissipative balancing circuits are state of the art, because they are simple and cost-effective. Unfavourable is their minimal degree of freedom and therefore the least starting points for a balancing strategy. They are only capable of discharging cells. Because of their dissipative nature, balancing is usually applied during charging to avoid additional losses. Three possible strategies can be realized with dissipative balancing circuits:

- *Top balancing* is applied at the end of a charging process. When the first cell-block in a serial string reaches its end-of-charge voltage, the charging process is stopped and the voltage difference between the cell-block with the lowest voltage and all other cell-blocks is measured after a certain relaxation time. Kindermann *et al.* showed that the relaxation time span in literature varies between 1 and 24 hours [14]. The relaxation time is necessary to let the overpotential of the cells decay allowing the measurement of the open-circuit voltage (OCV). In a next step, the cell-blocks with higher voltages are bypassed to discharge them to the voltage level of the cell-block with lowest cell potential. After that the battery is charged again until one of the cell-blocks reaches the end-of-charge voltage once more. This process can be applied repeatedly until a stop criterion. Normally a targeted voltage difference limit is met at the end of the charging process.
- *Continuous balancing* tries to even out the voltage differences during the charging process. This approach is more difficult than top balancing, since the cell's overpotential has to be considered. Consequently a model, e.g. an equivalent circuit model (ECM), is needed to even out the impedance caused voltage differences. This approach has the advantage of being less time consuming, since no extra time for cell relaxation is needed.
- *Bottom balancing* follows a similar strategy like top balancing. The cell-blocks are equalized at the end of a discharge period, when the first cell-block reaches the end-of-discharge voltage. After a certain relaxation time, the cell-blocks with the higher voltages are bypassed and discharged to the voltage level of the cell-block with the lowest voltage. Again, the relaxation time is necessary to let the overpotential of the cells subside, allowing to measure the OCV. This process is applied repeatedly until the voltage difference between the cell-blocks has reached a targeted limit. After that the balanced cell-blocks are charged again.

The range of the balancing current depends on the voltage spread between cell-blocks and the available time for balancing. The less time can be spared on balancing and the greater the inhomogeneities between cell-blocks are, the greater the balancing current has to be. For a typical application with a dissipative balancing circuit with bypass resistors, the balancing currents are fixed and below 200mA [15–18].This regime of the balancing current is not sufficient to influence the heat generation of a cell. The bypass transistor balancing circuit allows adapting the balancing current by regulating the transistors resistance. However, even if the balancing current is high enough, the temperature gradient could only be reduced by increasing the temperature of colder cells. Under moderate operation conditions, this will lead to a more homogeneous ageing but at the risk of accelerated ageing. Therefore, the second goal, a minimized temperature gradient between cell-blocks, is not achievable with dissipative balancing circuits.

2.3.2 Strategies for Non-Dissipative Balancing Circuits

Non-dissipative circuits are capable of redistributing charges between cells. Therefore, the balancing process does not waste all energy in excessive heat and can be applied during charging and discharging. Only a fraction of the redistributed energy is lost due to not ideal character of the balancing circuitry. Balancing voltage differences is achieved by transferring charges from cell-blocks with higher voltages to cell-blocks with lower voltages. Hence, the accessible capacity of a battery is increased. Since the initial variations between cells are small, the balancing effort is small as well but may rise with ageing. Balancing currents can be applied in all operation states. Hence, a model is required for taking the cell overpotential into account, just like in the case of continuous balancing.

In addition the redistribution of charges enables the non-dissipative circuits to influence the heat generation of the cell-blocks. This allows pursuing the goal of homogeneous and minimized ageing by reducing the load for cell-blocks at higher temperatures. The amount of current the balancing circuit has to handle is dependent on the cell characteristics. Bernadi *et al.* showed that the generated heat of a cell is linked to the polarization heat, the product of the cell's overpotential and current. The overpotential is caused by ohmic losses, charge transfer overpotential and mass transfer limitations, which are dependent on cell design and active materials. [19]

The strategy for the charge redistribution has to be carefully designed. Perusing both goals temperature and voltage balancing may not be congruent in every case. For example, a heated up cell-block may have a lower voltage than a cell-block at a lower temperature. To decrease the temperature gradient the load of the heated up cell-block would be reduced, which would increase the voltage imbalance. If the strategy has its focus on extending the accessible battery energy, the cell-block with the lower voltage may be charged with the additional energy of the heated up cell-block, which could increase the temperature gradient. A temperature gradient reduction can be achieved by heating colder cell as well. This will still lead to homogeneous ageing, but at the risk of accelerated ageing. A way to address both goals is to formulate an optimization problem; for example by minimizing a cost function f, like in Equation (1):

$$f = \Delta V + \Delta T \tag{1}$$

where ΔV is the maximal voltage gradient and ΔT the maximal temperature gradient between cell-blocks. In combination with a thermal and electrical model of the cell, a theoretical optimal current redistribution of the load can be calculated for the next time step. To achieve more accurate results, thermal interactions between cells and the cooling system have to be considered. Consequently, the model complexity rises very fast with growing cell numbers. The cost function and the objectives of the cost function may vary depending on the focus of the balancing strategy. For example, one of the terms in Equation (1) could be used as boundary condition or additional/other objectives, like minimized balancing losses, could be introduced. In their works, Altaf *et al.* [20–22] and Barreras *et al.* [23] give examples for the implementation of different balancing strategies with non-dissipative balancing circuits.

The efficiency of the balancing circuit is another influence factor. The converters used for the non-dissipative circuits, usually have a load dependent efficiency. When operated at relatively low loads compared to their maximal load, the converters can be very inefficient and behave almost like a dissipative circuit. Therefore, the design of the balancing circuit and the maximal and minimal loads the balancing circuit should handle plays an important role.

2.4 Conclusions

State of the art dissipative balancing circuits, like the bypass resistor circuit, are suitable for applications, if the following assumptions are met: Firstly, the thermal management is carefully designed avoiding temperature gradients between cell-blocks, which causes inhomogeneous cell ageing. Secondly, the cell parameter variation in capacity and resistance is and stays small enough during the battery's lifetime and thereby does not cause too much voltage deviation between cell-blocks, which limits the accessible capacity. Under these two assumptions the dissipated energy through balancing is minimal and the balancing effort and currents are relatively low. In addition, usually no models or complex strategies are needed for balancing.
If however one assumption is violated, the overhead for a non-dissipative balancing circuit can be justified, since it is capable of reducing voltage as well as temperature gradients between cell-blocks and thereby increasing the accessible capacity and guaranteeing homogeneous ageing. To realize a strategy pursuing both objectives, temperature and voltage gradient reduction, thermal and electrical cell parameters are necessary for modelling. The model complexity rises with the amount of cells in the battery and if interactions between cells and the cooling system are considered. Besides cell parameters, the converter design of the balancing circuit in combination with the load currents is vital.

2.5 References

[1] C. Guenther, B. Schott, W. Hennings, P. Waldowski, and M. A. Danzer, "Model-based investigation of electric vehicle battery aging by means of vehicle-to-grid scenario simulations," *Journal of Power Sources*, vol. 239, pp. 604–610, 2013.
[2] M. Naumann, R. C. Karl, C. N. Truong, A. Jossen, and H. C. Hesse, "Lithium-ion Battery Cost Analysis in PV-household Application," *Energy Procedia*, vol. 73, pp. 37–47, 2015.
[3] S. B. Peterson, J. Apt, and J. F. Whitacre, "Lithium-ion battery cell degradation resulting from realistic vehicle and vehicle-to-grid utilization," *Journal of Power Sources*, vol. 195, no. 8, pp. 2385–2392, 2010.
[4] 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.
[5] 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.
[6] 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.
[7] T. Baumhöfer, M. Brühl, S. Rothgang, and D. U. Sauer, "Production caused variation in capacity aging trend and correlation to initial cell performance," *Journal of Power Sources*, vol. 247, pp. 332–338, 2014.
[8] J. Marco, N. Kumari, W. Widanage, and P. Jones, "A Cell-in-the-Loop Approach to Systems Modelling and Simulation of Energy Storage Systems," *Energies*, vol. 8, no. 8, pp. 8244–8262, 2015.
[9] B. Kenney, K. Darcovich, D. D. MacNeil, and I. J. Davidson, "Modelling the impact of variations in electrode manufacturing on lithium-ion battery modules," *Journal of Power Sources*, vol. 213, pp. 391–401, 2012.
[10] M. Ouyang *et al.,* "A dynamic capacity degradation model and its applications considering varying load for a large format Li-ion battery," *Applied Energy*, vol. 165, pp. 48–59, 2016.
[11] J. Gallardo-Lozano, E. Romero-Cadaval, M. I. Milanes-Montero, and M. A. Guerrero-Martinez, "Battery equalization active methods," *Journal of Power Sources*, vol. 246, pp. 934–949, 2014.
[12] Institute of Electrical and Electronics Engineers; IEEE Power Electronics Society; Vehicular Technology Society; IEEE Vehicle Power and Propulsion Conference; VPPC, *IEEE Vehicle Power and Propulsion Conference (VPPC), 2011: 6 - 9 Sept. 2011, Chicago, IL, USA*. Piscataway, NJ: IEEE, 2011.
[13] Institute of Electrical and Electronics Engineers; IEEE Vehicle Power and Propulsion Conference; VPPC, *IEEE Vehicle Power and Propulsion Conference, 2008: VPPC '08 ; 3 - 5 Sept. 2008, Harbin, China*. Piscataway, NJ: IEEE, 2008.
[14] F. M. Kindermann, A. Noel, S. V. Erhard, and A. Jossen, "Long-term equalization effects in Li-ion batteries due to local state of charge inhomogeneities and their impact on impedance measurements," *Electrochimica Acta*, vol. 185, pp. 107–116, http://www.sciencedirect.com/science/article/pii/S0013468615306897, 2015.
[15] Analog Devices, "LTC6810-1/LTC6810-2 - 6-Channel Battery Stack Monitors (Rev. 0)," 2018.
[16] Analog Devices, "LTC6813-1 Multicell Battery Monitor," 2018.
[17] Texas Instruments, "bq769x0 3-Series to 15-Series Cell Battery Monitor Family for Li-Ion and Phospha datasheet (Rev. G)," 2016.
[18] Texas Instruments, "bq79606-Q1 SafeTI™ Precision Monitor With Integrated Hardware Protector for Automotive Battery Pack Applications," 2018.
[19] D. Bernardi, "A General Energy Balance for Battery Systems," *J. Electrochem. Soc.*, vol. 132, no. 1, p. 5, 1985.
[20] F. Altaf and B. Egardt, "Comparative Analysis of Unipolar and Bipolar Control of Modular Battery for Thermal and State-of-Charge Balancing," *IEEE Trans. Veh. Technol.*, vol. 66, no. 4, pp. 2927–2941, 2017.
[21] F. Altaf, B. Egardt, and L. Johannesson Mardh, "Load Management of Modular Battery Using Model Predictive Control: Thermal and State-of-Charge Balancing," *IEEE Trans. Contr. Syst. Technol.*, vol. 25, no. 1, pp. 47–62, 2017.

[22] F. Altaf, L. Johannesson, and B. Egardt, "2014 IEEE Vehicle Power and Propulsion Conference (VPPC): 27 - 30 Oct. 2014, Coimbra," (eng), 2014.
[23] J. V. Barreras *et al., 2014 IEEE Vehicle Power and Propulsion Conference (VPPC): 27 - 30 Oct. 2014, Coimbra*. Piscataway, NJ: IEEE, 2014.