A novel non-isolated active charge balancing architecture for lithium-ion batteries

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***Abstract* — Active charge balancing is an approved technique to implement high performance lithium-ion battery systems. Enhanced balancing speeds and reduced balancing losses are feasible compared to passive balancing. The new architecture proposed in this paper overcomes several drawbacks of other active balancing methods. It consists of only 2 non-isolated DC/DC converters. In combination with a MOSFET switch matrix it is able to balance arbitrary cells of a battery system at high currents. Adjacent cells can be balanced simultaneously. For the given setting, numerical simulations show an overall balancing efficiency of approx. 92.5%, compared to 89.4% for a stack-to-cell-to-stack method (St2C2St, bidirectional fly-back) at similar balancing times. The usable capacity increases from 97.1% in a passively balanced system to 99.5% for the new method.**

Keywords — Battery management system, Active charge balancing, Lithium-ion battery systems, Active balancing techniques

I. INTRODUCTION

Large lithium ion batteries consist of many single cells that are connected in series and in parallel to deliver the desired system voltage and energy capacity. The electric parameters of individual cells vary due to fabrication tolerances, ageing and temperature gradients inside the pack. Therefore, the usable capacity of a battery system is limited by its weakest cell or cell level and the remaining energy in the other cells stays untouched. Weaker cells reach charge and discharge limits earlier. The deviations increase with increased use of the battery [1]. Since the beginning of the use of lithium-ion technology, balancing circuits ensure to keep the charging process as safe as possible. Active balancing solutions are able to transfer charge between individual cells at high efficiency. They represent a promising possibility to enhance the energy efficiency and eco friendliness of lithium-ion battery systems when applied both during the charging and discharging process, as shown in Fig. 1. The left side illustrates the charging process. During passive balancing, the excess charge is dissipated and lost. On the contrary, during active balancing, the excess charge is transferred to other cells in the system. When implementing active balancing, the discharge time can be increased as shown on the right side of Fig. 1. Charge which would stay unused in the cell is transferred to another, weaker cell. This leads to an increase of the usable capacity of the battery.

A large number of methods and circuits was discussed in the literature in recent years. The superiority over passive balancing in terms of energy efficiency and speed has been proven in theory ([2], [3], [4]) and by measurement (see references in Table 1 and [5], [6], [7]). Despite the advantages, battery systems with active balancing are still rare in industrial applications. The reasons are manifold and range from higher component costs to reduced reliability and larger dimensions. Commonly, four basic topologies are distinguished: *Cell-to-cell*, *cell-to-stack*, *stack-to-cell* and *stack-to-cell-to-stack*, which is a combination of the previous two.

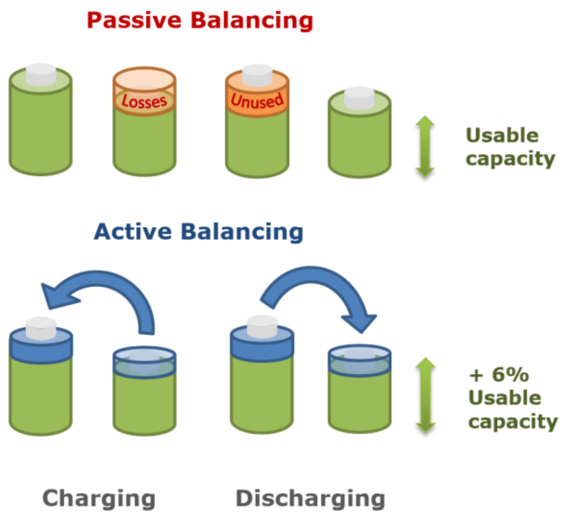

FIG. 1. BASIC FUNCTION PRINCIPLE OF ACTIVE CHARGE BALANCING

Apart from these standard topologies other circuits and types have been proposed in [8], [7] and [9]. For a general topology overview see [10] and [11].

This paper is the first to propose the use of two non-isolated DC/DC-converters and a switch matrix as a new approach to active charge balancing in lithium-ion battery systems. On the following pages the functionality and the estimated performance of the method is presented. Section II summarizes the state of art and available publications on non-isolated balancing methods. In section III, the new method is described in detail. The simulation settings and the balancing algorithm as well as the simulation results are given in section IV. Section V compares the proposed method to existing ones in terms of complexity and balancing performance.

II. State of the Art

As shown in [12], active balancing can increase the usable capacity of a battery system during the discharging process by 1% to 6%, depending on the cell and system parameters. In a comparison presented in [2] the *cell-to-cell* topology shows superior performance compared to any other active balancing methods in terms of balancing speed and efficiency. However, cell-to-cell balancers are technically challenging due to the numerous power paths. Two hardware realization options are available: Either with isolated power converters or with a non-isolated converter interfacing a floating capacitor tank.

Non-isolated methods for charge balancing reach high efficiencies at a small size. The most promising techniques proposed in literature are mentioned in Table 1. If available, the tested balancing current and the measured efficiency of the hardware are given as well.

Table 1: Overview of non-isolated active balancing methods

Architecture	**Max. balancing current**	**Max. balancing efficiency**
Single switched capacitor [13]	2 A	83 %
Single switched capacitor [14]	1 A	> 90 %
Switched inductors [15]	1 A	-
Switched inductors [16]	5 A	85 %
Series bidirectional converters [17]	-	-
PWM converters [10]	-	-
Switched capacitors [18]	-	-
Step-up converter [19]	-	-

For an efficiency overview of other active balancing methods see [14]

III. Description of the New method

The new active balancing method is called *Buck-In/Boost-Out*. In accordance with the used nomenclature, the description is *stack-to-cells-to-stack*. The balancing principle is based on the selective charging and discharging of a variable number of battery cells connected in series. A buck converter works as a charging unit, which transfers charge from the stack to the selected cells. Discharge is performed in the similar way via a boost converter.

The topology has a switch matrix to connect the desired cells with the converters. The corresponding switches must be blocking in both directions and can be realized with 2 MOSFETs each (see Fig. 2). The output voltage range of the buck converter and the input voltage range of the boost converter must be wide enough to cover the voltage range of 1 to n-1 cells. In this way, all cells can be actively charged and discharged up to the highest level in the stack. Simultaneous balancing of multiple cells is only possible for adjacent cells. For the uppermost cell, balancing takes place by accessing all cells below it.

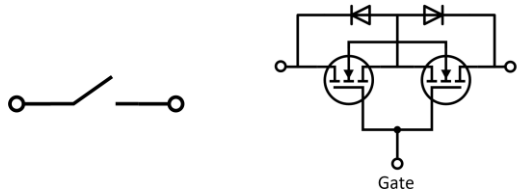

Fig. 2. AC switch and N-MOSFET equivalent circuit

Fig. 3 shows the discussed balancing method for a battery system with n cells in series. The operating parts are dyed to indicate the working principle. The buck converter delivers energy from the stack through the switch *Sw_A2* to *Cell 1* and *Cell 2*. These are charged with the converter output current I_{Buck}. Simultaneously, the boost converter discharges *Cell 1* through *Sw_B1* with the converter input current I_{Boost}. Given that $I_{Buck} = I_{Boost}$, the sum of the current of *Cell 1* is 0 A and *Cell 2* is charged with I_{Buck} (positive balancing). Generally, cells are charged by connecting the buck converter on a higher position than the boost converter. Discharging is carried out in reverse order.

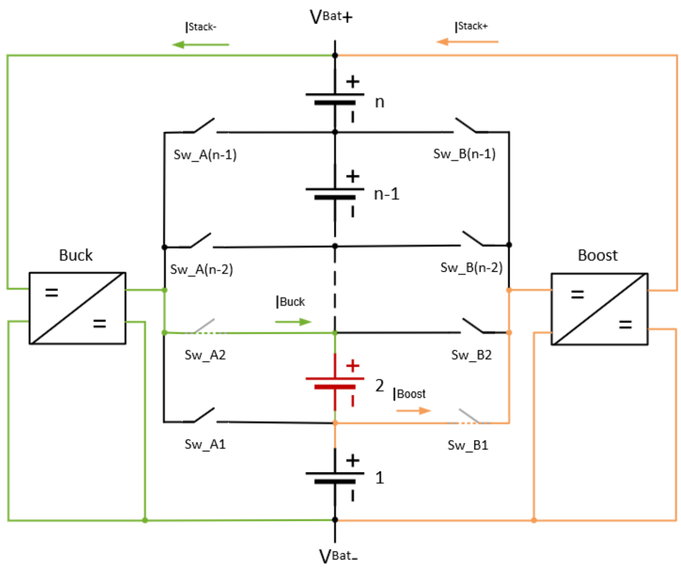

Fig. 3. Buck-In/Boost-Out Active balancing

The resulting stack current is the sum of the buck input current and the boost output current. It is a function of the converter efficiencies (η_{Buck} and η_{Boost}), the average cell voltage U_{Cell} the number of cells n and the state of the switch matrix (Buck output position: x, Boost input position: y):

$$I_{Stack-} = \frac{I_{Buck} \cdot x \cdot U_{Cell}}{\eta_{Buck} \cdot U_{Stack}}. \qquad (1)$$

$$I_{Stack+} = \frac{I_{Boost} \cdot y \cdot U_{Cell} \cdot \eta_{Boost}}{U_{Stack}}. \qquad (2)$$

Assuming $U_{Stack} = n\,U_{Cell}$ and $I_{Buck} = I_{Boost} = I_{Bal}$, it follows that

$$I_{Stack} = I_{Stack+} - I_{Stack-} = \frac{I_{Bal}\left(y \cdot \eta_{Boost} - \frac{x}{\eta_{Buck}}\right)}{n}. \quad (3)$$

Table 2 shows different possible balancing states of the circuit. In the first row, the cell numbers are listed that are selected for balancing. The second row states whether the cell is charged or discharged. Row 3 and 4 indicate if both converters are necessary for balancing and row 5 gives the correct setting of the switch matrix.

TABLE 2: BALANCING MODES

Desired cell for balancing	Balancing direction	Buck converter	Boost converter	Active switch
#2	Charge	I_{Bal}	I_{Bal}	A2, B1
#3 & #4	Charge	I_{Bal}	I_{Bal}	A4, B2
#1	Charge	I_{Bal}	-	A1
#n	Discharge	I_{Bal}	-	A(n-1)
#1 & #2	Discharge	-	I_{Bal}	B2
#2	Discharge	I_{Bal}	I_{Bal}	A2, B3

The converter power and total losses depend on the number of cells in the stack *n* and the position of the balanced cell inside the stack. They increase with increasing number of cells and higher position. $\vec{\eta}_{Buck}$ and $\vec{\eta}_{Boost}$ are the corresponding efficiency vectors. For any cell, except the topmost one, the overall balancing efficiency for charging at the cell position *j* (positive balancing) is

$$\eta_{BalC_j} = 1 - j \cdot \frac{1-\eta_{Buck_j}}{\eta_{Buck_j}} - (j-1) \cdot (1 - \eta_{Boost_{j-1}}) . \quad (4)$$

For discharging (negative balancing) of cells *1* to *j-1*, the efficiency calculates as follows:

$$\eta_{BalD_j} = 1 - (j-1) \cdot \frac{1-\eta_{Buck_{j-1}}}{\eta_{Buck_{j-1}}} - j \cdot \left(1 - \eta_{Boost_j}\right). \quad (5)$$

For the topmost cell *n*, only one converter is required to perform the balancing. The efficiencies for charging and discharging are calculated as:

$$\eta_{BalC_n} = 1 - (n-1) \cdot \left(1 - \eta_{Boost_{n-1}}\right), \quad (6)$$

$$\eta_{BalD_n} = 1 - (n-1) \cdot \frac{1 - \eta_{Buck_{n-1}}}{\eta_{Buck_{n-1}}}. \quad (7)$$

Equations (4)-(7) are valid only for the balancing of one cell, not of a group of adjacent cells.

IV. SIMULATION AND PERFORMANCE EVALUATION

A. *Simulation settings*

The numeric simulations were done in MATLAB. The cell capacity values are random numbers as a function of the chosen cell parameters (see Table 3). A MATLAB script processes these values according to the balancing algorithm shown in Fig. 4. The battery parameter used in the simulation are given in Table 3.

TABLE 3: SIMULATION CELL PARAMETERS

Cell parameter		Value
Nominal capacity	C_{nom}	100 Ah
Nominal voltage	U_{nom}	3.7 V
Standard deviation	σ_0	2…3 %
Number of cells	n	8
Balancing current	I_{bal}	10 A

B. *Balancing algorithm*

The balancing algorithm is described in Fig. 4. First, the difference of each cell to the mean value is calculated. Then the biggest group of cells for simultaneous balancing is defined. The following steps are repeated assuming a time step of 1 s:

- Charge or discharge the selected cells by $I_{Bal}\,As$ (applying balancing for 1 second)
- Discharge or charge all cells in the system with the resulting stack current calculated in (3)
- Recalculate the mean and delta values
- Repeat until the capacity of one of the active cells reaches the mean value

This sequence repeats until the deviation reaches less than $0.2\sigma_0$. After 10’000 simulations of each parameter set, the mean value of all individual simulation results is computed.

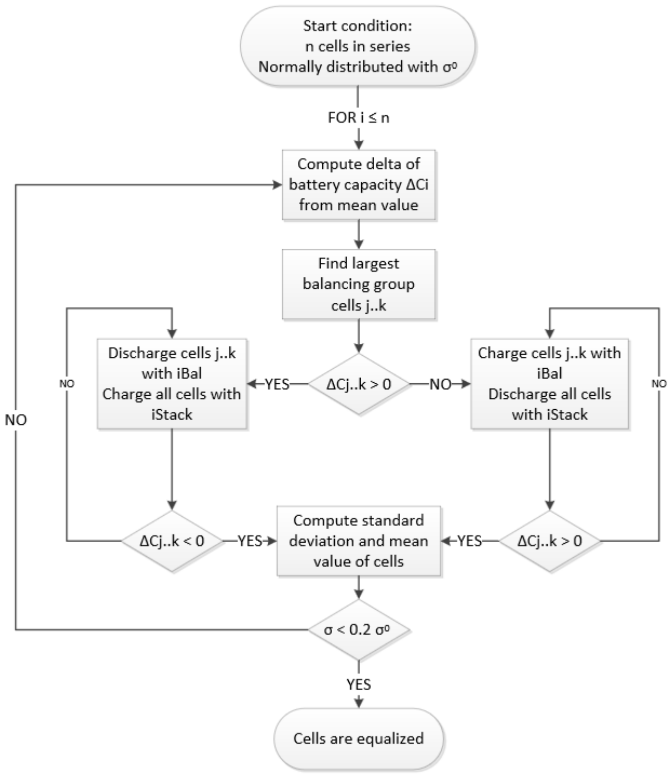

FIG. 4. ALGORITHM FOR THE CELLS-TO-STACK-TO-CELLS BALANCING SIMULATION

C. Converter efficiencies

The efficiency values of the synchronous buck and boost converter are obtained by calculation. Conduction losses P_C, switching losses P_{SW}, ohmic losses P_R and gate drive supply P_Q are taken into account according to (8). Fig. 5 shows the surface plot of the overall balancing efficiency.

$$\eta_{Converter} = \frac{I_o \cdot V_o}{(I_o \cdot V_o + P_c + P_{sw} + P_R + P_Q)} \tag{8}$$

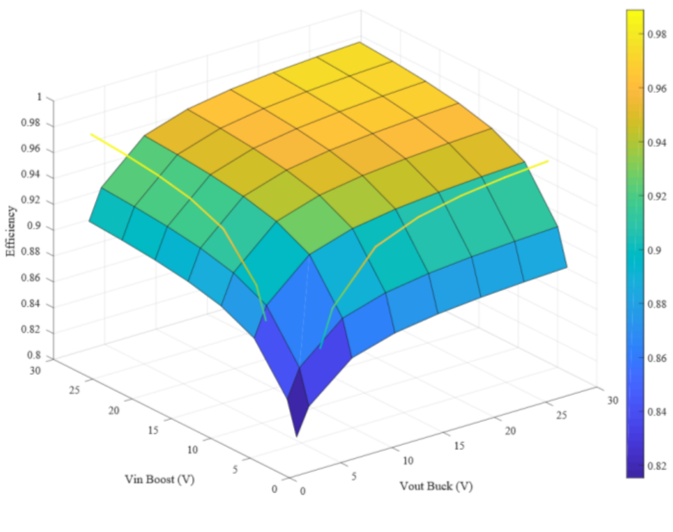

FIG. 5. CALCULATED BUCK AND BOOST EFFICIENCIES (LINES) AND OVERALL CONVERTER EFFICIENCY INCLUDING THE SWITCH MATRIX (SURFACE)

The converter efficiencies obtained from Fig. 5 and used in the simulation in section D are given in Table 4. For 10 A of balancing current a converter power of 256 W is required.

TABLE 4: CONVERTER CHARACTERISTICS

Output to cell *j* **Input from cell *j***	η_{Buck_j}	η_{Boost_j}	**Max. converter power @ i_{Bal} = 10 A and U_{Cell} = 3.65 V**
1	0.921	0.936	39 W
2	0.959	0.967	75 W
3	0.972	0.978	111 W
4	0.979	0.983	147 W
5	0.983	0.987	183 W
6	0.986	0.989	220 W
7	0.988	0.990	256 W

D. Simulation results

Fig. 6 shows the different cell capacities during the simulated balancing process. In the beginning, the cell capacities are normally distributed with an average capacity of 100% and a standard deviation of 2%. The algorithm achieves to reduce the imbalance continuously until the balancing end is reached at $0.2\sigma_0$.

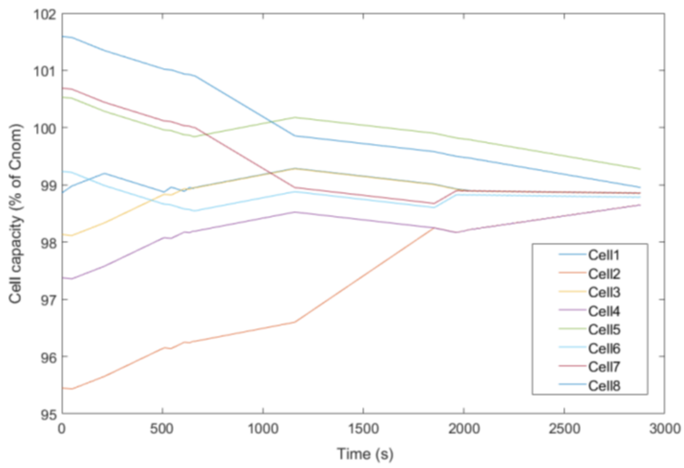

FIG. 6. SIMULATED BALANCING PROCESS OF 8 CELLS WITH NORMALLY DISTRIBUTED BATTERY CELL CAPACITIES (FOR $\sigma 0 = 2\%$)

The batch simulations are executed with different battery parameter settings. The arithmetic mean of each 10'000 simulation results is shown in Table 6.

TABLE 5: SIMULATION RESULTS FOR DIFFERENT CELL SETTINGS

Parameter / Settings	**σ_0=2% 7 cells**	**σ_0=3% 7 cells**	**σ_0=2% 8 cells**	**σ_0=3% 8 cells**
Average balancing time	3511 s	5613 s	3919 s	6270 s
Balancing efficiency	0.926	0.925	0.926	0.928
Usable capacity (active)	99.4%	99.3%	99.5%	99.3%
Usable capacity (passive)	97.2%	95.8%	97.1%	95.7%

V. COMPARISON TO EXISTING METHODS

A. Part count

Most active balancing topologies use a power electronic converter per cell or cell level, which is responsible for the charge transfer to or from the cell. By reducing the number of converters, it is possible to reduce the number of components required and thus also the costs. If the savings flow into the remaining hardware, an increase in efficiency will be achieved. Table 6 gives an overview of the required components of different balancing methods. For the new Buck-In/Boost-Out method the amount of high frequency switching devices is just 2, respectively 4 in case of a synchronous design. The MOSFETs of the switch matrix can be operated with a low power gate driver as they are turned on and off only every couple of seconds. Table 6 gives an overview of the required components for different architectures.

TABLE 6: COMPONENT LIST FOR SEVERAL ACTIVE BALANCING ARCHITECTURES (DATA FROM [10] AND [19])

Architecture	**FET**	**Sw**	**R**	**C**	**L**	**D**
Dissipative	0	n	n	0	0	0
PWM Converters	2n-2	0	0	1	n-1	0
Switched capacitors	2n	0	0	n-1	0	0

Single switched capacitor	0	2n	0	1	0	0
Step up converter	n	0	0	n	n	n
Multiple transformer (Cell2stack)	n	0	0	0	n	n
Multiple transformer (Stack2cell)	1	0	0	0	n	n
Bidirectional multiple transformer (St2C2St)	2n	0	0	0	n	0
Buck-In/Boost-Out (This work)	2/4[1]	2n-2	0	2	2	2/0

FET: MOSFET for high switching frequency, Sw: AC-switch (see Fig. 2), R: Power resistor, C: Capacitor, L: Inductor, D: Diode
[1] Non-synchronous design / Synchronous design

B. *Energy efficiency and balancing speed*

The balancing performance of the *Buck-in/Boost-Out* architecture is compared to a *stack-to-cell-to-cell* (St2CSt) method featuring bidirectional fly-back converters based on the LTC3300-1 active balancing IC (see Table 7). A transfer efficiency of 90% is assumed for both operation modes of the fly-back converter according to the data sheet [20]. The balancing current is chosen to be 2.5 A. This is ¼ of the balancing current of the investigated method. For both methods, the sum of all converter currents is 20 A.

TABLE 7: PERFORMANCE COMPARISON OF ACTIVE AND PASSIVE BALANCING

Parameter	This work	St2C2St	Passive
Average balancing time	3919 s	3601	-
Balancing losses	7.4%	10.6%	n.a.
Usable capacity	99.5%	99.3%	97.1%

8 cells, normally distributed, σ_0 =2%, average of 10'000 simulation results

VI. CONCLUSION

This paper introduces a novel active balancing architecture called *Buck-In/Boost-Out*. Its non-isolated design allows the use of high-efficiency DC/DC-converters. The type of balancing shows similarities to the bidirectional multiple transformers method *stack-to-cell-to-stack*. A comparison based on numerical simulations shows a reduction of balancing losses in the range of 30%. Hence, more charge can be extracted from a battery pack when balancing takes place during the discharging process. Every cell except the top cell can be accessed directly. Unlike other active balancing methods, the cell voltage does not influence the balancing paths in any way.

The drawbacks of the new method are the high power rating of the converters involved. For an 8 cells battery system, the required converter power to deliver 10 A of balancing current is more than 250 W. Furthermore, the converter power ratings and the balancing efficiencies depend on the the number of cells in series. 7 or 8 cells applications seem to be well suited whereas the disadvantages might outweigh the benefits in battery packs with more than 16 cells.

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