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Capacitor-Based Active Cell Balancing for Electric Vehicle Battery Systems: Insights from Simulations

Research paper

Daniel Marcin*, Milan Lacko, Dávid Bodnár, Lukáš Pancurák

Department of Electrical Engineering and Mechatronics, Faculty of Electrical Engineering and Informatics, Technical University of Košice, Košice, Slovakia

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Abstract: Cell balancing, a critical aspect of battery management in electric vehicles (EVs) and other applications, ensures a uniform state of charge (SOC) distribution among individual cells within a battery pack, enhancing performance and longevity while mitigating safety risks. This paper examines the effectiveness of capacitor-based active cell-balancing techniques using simulations under dynamic loading conditions. Utilising MATLAB and Simulink, various circuit topologies are evaluated, considering real-world cell parameters and open-circuit voltage (OCV) curve modelling. Results indicate that advanced configurations, such as double-tiered switched-capacitor balancing, offer improved balancing speed and efficiency compared to conventional methods. However, challenges such as transient events during charging and discharging phases underscore the need for further research. By leveraging simulations and experimental data, researchers can refine cell-balancing strategies, contributing to the development of safer, more efficient battery systems for EVs and beyond. This study underscores the importance of systematic analysis and optimisation in advancing cell-balancing technology for future energy-storage applications.

Keywords: *battery • electric vehicle • battery management system • active cell balancing • capacitor*

1. Introduction

Cell balancing, an essential aspect of battery management in electric vehicles (EVs) and various other applications, plays a pivotal role in enhancing the battery pack performance, longevity and safety. This process, also known as cell equalisation, aims at harmonising the state of charge (SOC) across individual cells within a battery pack, ensuring optimal operation and preventing potential issues such as overcharging or overdischarging (Andrea, 2010; Plett, 2015).

In the realm of battery technology, two primary methods are commonly employed for cell balancing: passive balancing and active balancing. Passive balancing, characterised by the use of dissipative components like resistors, dissipates excess energy as heat to achieve balance among cells (Wei and Zhu, 2009). On the other hand, active balancing involves the transfer of charge between cells using energy-storage components such as capacitors, inductors or transformers, enabling more efficient energy utilisation and faster balancing (Qi and Dah-Chuan Lu, 2014). Designing effective cell-balancing circuits necessitates a careful balance between performance, cost and complexity. The selection of balancing techniques and circuitry configuration depends on various factors, including the type of battery cells, application requirements and cost considerations (Weicker, 2013).

Passive balancing, despite its simplicity and low cost, suffers from energy losses and slower balancing rates, making it less suitable for certain applications (Wei and Zhu, 2009). In contrast, active balancing methods offer faster and more efficient balancing but require more complex configurations and control algorithms.

Among active balancing methods, capacitor-based techniques stand out for their efficiency and flexibility. Switched-capacitor balancing, double-tiered switched-capacitor balancing and other advanced configurations

* *Email: daniel.marcin@tuke.sk*

utilise capacitors to facilitate charge transfer between cells, improving balancing speed and effectiveness (Caspar et al., 2018; Takeda and Koizumi, 2017).

In this article, which is an extended article from the EDPE 2023 conference, we present simulation results comparing the performance of different capacitor-based active cell-balancing circuits under dynamic loading conditions. By integrating real-world cell parameters and open-circuit voltage (OCV) curve modelling into our simulations, we aim to provide insights into the effectiveness of these balancing techniques in practical scenarios (Marcin et al., 2023).

As the demand for high-performance, reliable battery systems continues to rise, advancements in cell-balancing technology remain paramount. Through systematic analysis, simulation and experimentation, researchers can drive innovations in cell-balancing techniques, ultimately contributing to the development of safer, more efficient battery solutions for diverse applications.

2. Cell Balancing

Cell balancing, also known as cell equalisation, is a crucial process in managing battery packs, aimed at balancing the charge levels of individual cells to ensure uniformity across the entire pack (Plett, 2015). A balanced battery pack is achieved when all the cells reach the same SOC at some stage during their operational cycle (Andrea, 2010). Failure to achieve this balance indicates differences in the SOC among cells, necessitating individual adjustments to restore equilibrium. Common balancing methods include passive and active techniques.

Passive balancing, often termed dissipative balancing, involves the utilisation of passive components like resistors to dissipate the excess energy as heat. Active balancing, also known as non-dissipative balancing, facilitates the transfer of charge from cells with higher SOC to either cells with lower SOC or auxiliary circuits.

Ensuring balance among battery cells connected in series is crucial, due to the situation illustrated in Figure 1. With passive balancing, energy from the cells with higher SOC needs to be discharged via resistors to equalise with the lowest SOC cell. Active balancing allows for energy redistribution among cells. Balancing between cells with resistors is not possible because it is not an active component for storing energy. Therefore, the energy can only be dissipated as heat and cannot be transferred to another cell. Without balancing, the battery pack could reach a critical state where one cell is at a lower voltage limit while another is at a higher limit, rendering the pack unusable (Plett, 2015).

2.1. Design of cell balancing

Given the necessity of replicating balancing circuits for each cell, expanding the battery-management system’s balancing capability has the potential to significantly increase system costs due to the multiplication of required components. Thus, appropriately sizing the balancing circuitry is crucial to maintain battery performance, prevent divergence and minimise unnecessary expenses (Weicker, 2013).

Alternatively, considering the standby power of the active balancing circuitry may exceed the heat dissipation from passive balancing in battery packs with minimal cell parameter variations. Active balancing is particularly advisable in scenarios where the duration of low-current passive balancing would be impractical or when high-current passive balancing could generate problematic heat (Andrea, 2010).

Active cell balancing techniques fall into two categories. The first category involves topologies that do not necessitate complex switching algorithms, regulating energy transfer between cells through pulse-width modulation (PWM) switching. The second category encompasses topologies employing intelligent algorithms to select cells for discharging or charging based on state analysis to balance overall cell voltage or SOC.

Figure 1. Battery pack from left to right: without balancing, with passive balancing, with active balancing.

Advanced control logics like fuzzy logic, neural networks and model predictive control can enhance the speed and efficiency of balancing algorithms. Incorporating these techniques optimises the balancing process, enabling quicker and more precise cell balancing (Leso et al., 2018; Pancurák et al., 2023; Pastor et al., 2019).

2.2. Passive cell balancing

Passive cell balancing involves dissipative resistors that remove energy from specific cells, making it the simplest and most economical balancing method. Cells with higher SOC are discharged through shunt resistors controlled by specific switches (Wei and Zhu, 2009). Alternatively, passive balancing can employ fixed resistors without additional switches, with continuous current flowing through them. Balancing occurs without active control, as dissipative currents are proportional to cell terminal voltages. However, the slow balancing pace may lead to certain cells being overcharged in a short period (Jiang et al., 2020).

The effectiveness of this method depends on factors such as shunt resistor size, design and control algorithms managing the balancing process. While properly designed passive balancing systems can maintain balance in a battery pack, they may not always be preferred over active balancing methods. High energy losses represent a significant disadvantage of passive cell balancing, potentially reducing battery pack energy efficiency. Despite this drawback, it remains a widely adopted method in EV applications due to its simplicity, low cost and ease of implementation (Wei and Zhu, 2009).

2.3. Active cell balancing

Active balancing methods have emerged in a way to mitigate energy losses associated with passive balancing. These methods involve using energy-storage components such as capacitors, inductors, or transformers to accumulate charges from the cells with high SOC and transfer them to the cells with low SOC. While active balancing enables more efficient battery energy utilisation in certain scenarios, it requires more complex configurations and control algorithms compared to passive methods (Carter et al., 2020; Qi and Dah-Chuan Lu, 2014).

There are four primary active balancing techniques.

- Cell to cell: transfers energy between adjacent cells,
- Cell to battery: extracts energy from highly charged cells and distributes it across the entire battery,
- Battery to cell: draws energy from the entire battery and supplies it to the least charged cells,
- Bidirectional: facilitate energy flow either from cell to battery or vice versa, depending on requirements.

Cell-to-cell balancing suits small batteries, while cell-to-battery balancing is the simplest and most efficient method. Battery-to-cell balancing is optimal when employing a charger with the same number of outputs as cells. Bidirectional balancing proves ideal for redistributions (Andrea, 2010).

3. Capacitor-Based Active Cell Balancing

Capacitor-based active balancing methods employ capacitors as energy-storage components, typically connected in parallel to the cells (Caspar et al., 2018). The first developed technique, switched-capacitor balancing, utilises fewer capacitors and simple PWM control algorithms but can result in long balancing times, especially when more cells are connected in series (Pascual and Krein, 1997). To enhance the speed of balancing, additional structures have been introduced, such as double-tiered, chain, parallel, delta, and mesh structures, enabling more efficient charge transfer between cells. Modularised designs, including modularised switched-capacitor balancing and modularised double-tiered switched-capacitor balancing, have also been devised, incorporating extra capacitors to balance adjacent cell groups. Single capacitor balancing can directly balance cells with the highest and lowest SOC, although it requires more complex control algorithms.

3.1. Switched-capacitor balancing

Switched-capacitor balancing, as depicted in Figure 2 (a), operates by applying the same PWM signals to all switches, causing them to alternate between on and off states at the same frequency (Pascual and Krein, 1997). Each capacitor is connected to two adjacent cells in a repetitive manner, facilitating the transfer of energy from cells with higher voltage to those with lower voltage. The control method for switched-capacitor balancing is

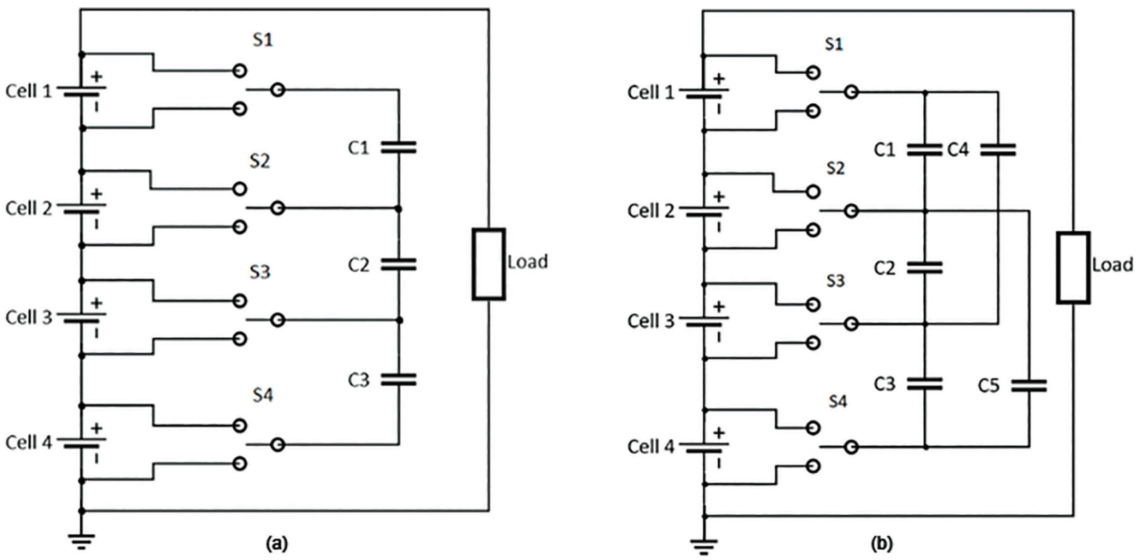

Figure 2. Switched-capacitor balancing (a), double-tiered switched-capacitor balancing (b).

straightforward and does not require information about the cell's SOC. However, the balancing process can be time-consuming due to two primary reasons. Firstly, as the balancing nears completion, the voltage difference between the adjacent cells becomes minimal, making it challenging to charge capacitors and transfer charges. Secondly, energy can only be exchanged between two adjacent cells within one balancing cycle. When transferring energy between cells that are far apart, multiple balancing cycles are necessary (Baughman and Ferdowsi, 2005).

3.2. Double-tiered switched-capacitor balancing

Double-tiered switched-capacitor balancing involves the use of two layers of capacitors, as illustrated in Figure 2 (b) (Takeda and Koizumi, 2017). The first layer consists of capacitors C1, C2, and C3, while the second layer comprises capacitors C4 and C5. Similar to the switched-capacitor balancing method, the same PWM signals are applied to all switches. In the case of a voltage difference between cell 1 and cell 3, energy can be directly transferred through capacitor C4 instead of going through C1 and C2. By utilising these charge-transfer shortcuts, the balancing speed can be enhanced, and the efficiency of balancing can be improved by reducing the number of energy conversions required. However, a drawback of this approach is the increased use of capacitors, leading to higher balancing circuit costs and a larger battery size (Baughman and Ferdowsi, 2005). Additional capacitor can be added to this structure to reduce the balancing time between the topmost cell and the undermost cell (Paul and Sreejith, 2022).

3.3. Chain structure switched-capacitor balancing

In switched-capacitor balancing, when the first and last cell require balancing, charges must pass through each capacitor in sequence. To expedite this process, a chain structure switched-capacitor balancing technique employs an additional capacitor that directly connects the cells at both ends (Figure 3 (a)). When balancing is required, S1–S4 switches are initially turned on, while SC1 and SC2 switches are activated and SC3 and SC4 are deactivated. Subsequently, S1–S4 switches are turned off, SC1 and SC2 switches are deactivated, and SC3 and SC4 are activated. Cell 1 and Cell 4 are balanced directly with capacitor C0, while adjacent cells are balanced using C1, C2 and C3 capacitors. This configuration reduces the longest distance between two balanced cells by half. However, this balancing topology is unable to balance cells at any of the positions, resulting in reduced balancing speed and efficiency as the number of series-connected cells increases (Kim et al., 2014).

3.4. Parallel structure switched-capacitor balancing

Parallel structure switched-capacitor balancing enables direct balancing of two cells at any position. In this configuration, as depicted in Figure 3 (b), a single capacitor is connected between cell 1 and any other cell. The balancing process is similar to switched-capacitor balancing. With this balancing circuit, any two cells can be connected through one or two capacitors, resulting in improved balancing speed. However, only cell one can be balanced with other cells using a single capacitor. For other pairs of cells, balancing requires two or more capacitors connected in series, which increases the series equivalent resistance and leads to higher energy losses (Ye et al., 2017).

3.5. Delta structure switched-capacitor balancing

Delta structure switched-capacitor balancing provides another approach to directly balance two cells at any position by connecting each pair of cells with a single capacitor, as illustrated in Figure 4 (a). This method offers a high balancing speed and efficiency. However, the number of capacitors required is 0.5 ($N^2 - N$) where N represents the number of series-connected cells. As the number of cells increases, the capacitor count grows rapidly, resulting in

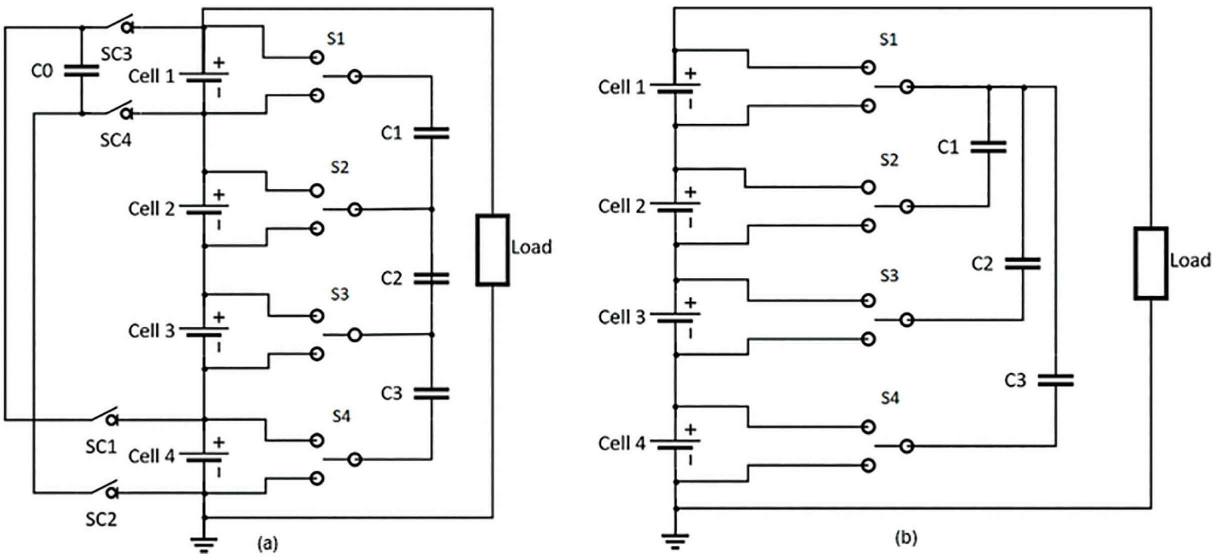

Figure 3. Chain structure switched-capacitor balancing (a), parallel structure switched-capacitor balancing (b).

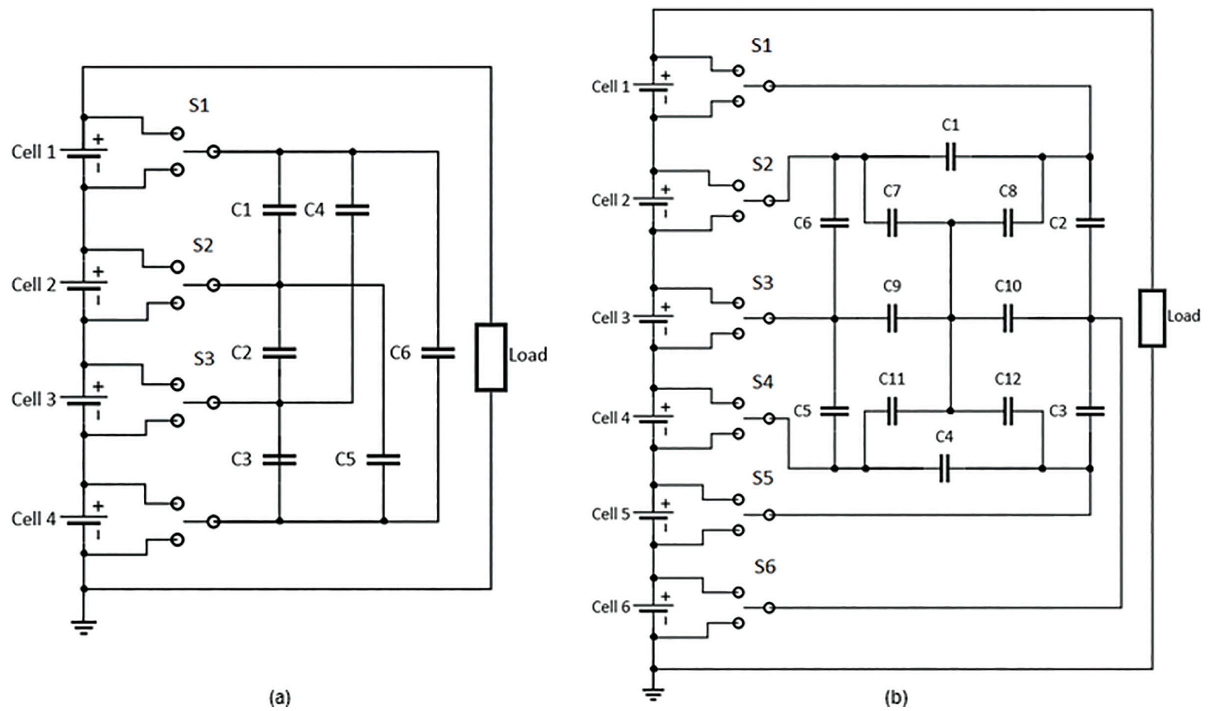

Figure 4. Delta structure switched-capacitor balancing (a), mesh structure switched-capacitor balancing (b).

higher costs. Additionally, the use of multiple layers of capacitors in the balancing circuit increases the overall size of the battery (Shang et al., 2018).

3.6. Mesh structure switched-capacitor balancing

Mesh structure switched-capacitor balancing, depicted in Figure 4 (b), employs simultaneous switching of all switches using the same PWM signals during the balancing process. This allows for the balancing of both adjacent and non-adjacent cells. Half of the paths have a single capacitor between two cells, while the other half have two capacitors. The total number of capacitors used in the balancing circuit is $2N$, where N is the number of series-connected cells. The mesh structure represents a compromise between the parallel structure and the delta structure, offering fewer energy losses compared to the parallel structure while using fewer capacitors than the delta structure. However, this method still needs a complex balancing circuit resulting in larger battery size (Shang et al., 2019).

3.7. Single switched-capacitor balancing

Single switched-capacitor balancing, depicted in Figure 5, offers the advantage of employing advanced control algorithms instead of PWM switching. The SOC of each cell is continuously calculated and monitored. When the maximum SOC difference among all cells exceeds a predetermined threshold, the balancing process is initiated. The highest and lowest SOC cells are identified, and the corresponding switches are activated to connect these cells with a capacitor. This enables the transfer of energy from the cell with the highest SOC to the one with the lowest SOC. The balancing process finishes when all cells have an SOC difference below the threshold. The speed of this method is notably fast when only two cells have a significant SOC difference, regardless of their positions. However, if there is a variation in the SOC across all cells, the balancing time will be much longer as only two cells can be balanced in each cycle (Daowd et al., 2014).

3.8. Other methods of balancing

Another method of more complex capacitor-based active cell balancing is using the combination of mesh structure and double-tiered structure. This hybrid approach offers improved balancing speed and efficiency compared to both individual methods. However, due to its combination, its price is also higher (Fukui and Koizumi, 2013). Modularised switched-capacitor is another way of improving the balancing performance. It is similar to the switched-capacitor structure. There are additional N switches and one additional capacitor. Modularised switched-capacitor can also be implemented to the double-tiered structure (Takeda and Koizumi, 2017). For further research, capacitor-based balancing techniques were selected due to their simplicity, low cost and lower weight compared to inductor- or transformer-based balancing.

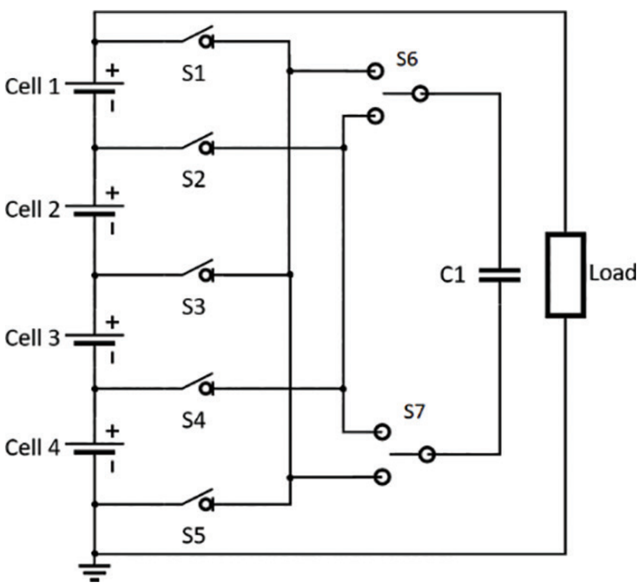

Figure 5. Single switched-capacitor balancing.

4. Simulations and Results

In order to develop a modular battery system, we performed simulations on various capacitor-based active cell balancing circuits. Among them, the switched-capacitor balancing circuit shown in Figure 2 (a) was our initial choice. Furthermore, we simulated the double-tiered switched-capacitor circuit depicted in Figure 2 (b). Lastly, we extended the second simulation by adding an additional capacitor across the first and last cells. This circuit is shown in the simulation model depicted in Figure 6. Simulations were performed in MATLAB and Simulink programs (Bodnár et al., 2023; Frivaldský, 2020).

4.1. Modelling, parameters and simulation data for comparison of balancing with different topologies

Data of manufacturer MOLICEL (Taipei, Taiwan) with model number INR18650-P26A were used for simulation battery cell parameters. For our purpose, we simulated on 12 cells connected in series. Simscape models of battery cells, ideal switch, and capacitors were used for our purpose. Simulation parameters are shown in Table 1.

The switches in the circuit are connected to two PWM signals named s1 and s2, operating at a frequency of 1 kHz. Signal s1 controls the switches with odd numbers, while signal s2 controls the switches with even numbers.

The simulation involved cells with an initial four percentage points imbalance arranged in a random order. To create more challenging conditions for balancing, the cells with the highest and lowest SOC were not placed adjacent to each other. The initial SOC values for all cells can be found in Table 2 and are the same for all the simulations. The simulations were carried out for a duration of 2,000 s. We compared the results of the simulations

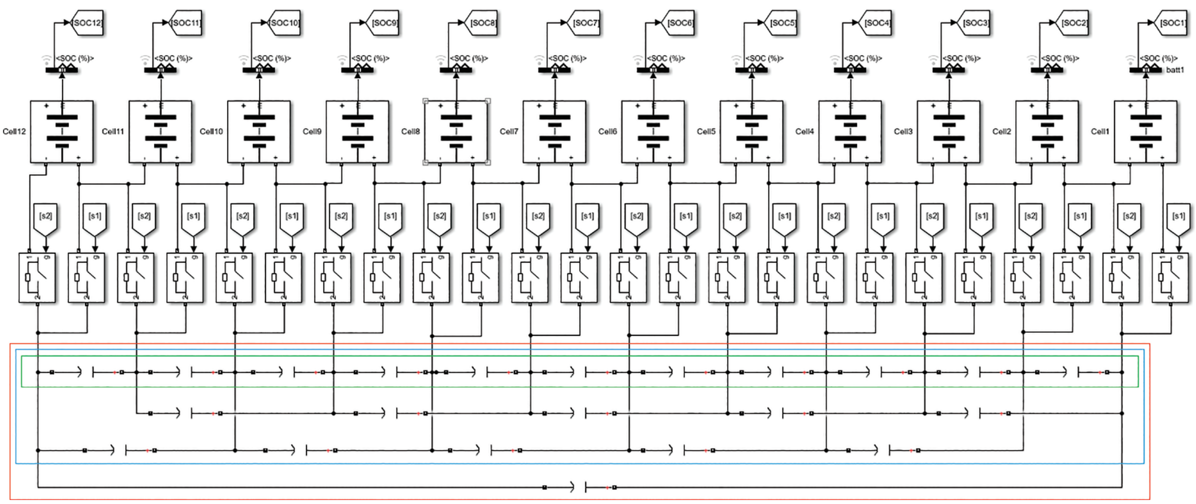

Figure 6. MATLAB Simulink simulation model of double-tiered switched-capacitor with additional capacitor with 12 cells in series (green – switched capacitors, blue – double-tiered switched capacitors, red – double-tiered switched-capacitor with additional capacitor). SOC, state of charge.

Table 1. Simulation parameters data for comparison of balancing with different topologies.

Parameter	Value	Unit
Battery nominal voltage	3.6	V
Battery capacity	2.6	Ah
Battery response time	0.5	s
Battery internal resistance	13.85	mΩ
Capacitor capacitance	50	mF
Switching frequency	1	kHz
Simulation time	2,000	s

when the difference between the lowest and highest SOC was set at one percentage point. There is no load applied to the battery pack in these simulations.

4.2. Results with switched-capacitor

In the first simulation, the switched-capacitor circuit shown in Figure 2 (a) was implemented using MATLAB Simulink. The model from Figure 6 was modified to match this circuit, with the additional capacitors removed. The simulation results revealed that a one percentage point imbalance was achieved in 1312 s. The cell with the highest SOC was Cell 1, and the cell with the lowest SOC was Cell 7. These simulation results are depicted in Figure 7 (a).

4.3. Results with double-tiered switched-capacitor

In the second simulation, we similarly implemented the double-tiered switched-capacitor circuit from Figure 2 (b) in MATLAB Simulink. The simulations revealed that a one percentage point imbalance was achieved in 1186 s, as shown in Figure 7 (b). As expected, this circuit, with its additional layers of capacitors, proved to be faster than the

Table 2. Cell SOC values across simulations of balancing with different topologies.

Cell	Initial value	Switched-capacitor balancing		Double-tiered switched-capacitor balancing		Double-tiered switched-capacitor balancing with additional capacitor	
Difference highest, lowest SOC [%]		1	0,72	1	0,68	1	0,65
Time [s]		1312	2000	1186	2000	1195	2000
				SOC [%]			
1	**98,00**	**96,48**	**96,39**	**96,45**	**96,33**	**96,43**	**96,31**
2	95,10	96,40	96,35	96,36	96,30	96,34	96,28
3	96,40	96,34	96,28	96,33	96,24	96,30	96,22
4	97,00	96,23	96,18	96,22	96,16	96,20	96,13
5	95,50	96,04	96,05	96,03	96,05	96,01	96,02
6	96,00	95,88	95,92	95,91	95,94	95,88	95,91
7	**94,00**	**95,48**	95,67	**95,45**	95,71	**95,43**	95,68
8	97,30	95,71	95,71	95,74	95,74	95,72	95,72
9	94,50	95,58	**95,66**	95,56	**95,68**	95,53	**95,66**
10	96,20	95,75	95,74	95,77	95,75	95,75	95,73
11	94,70	95,71	95,75	95,68	95,74	95,66	95,72
12	96,89	95,89	95,80	95,89	95,79	95,88	95,78

SOC, state of charge.

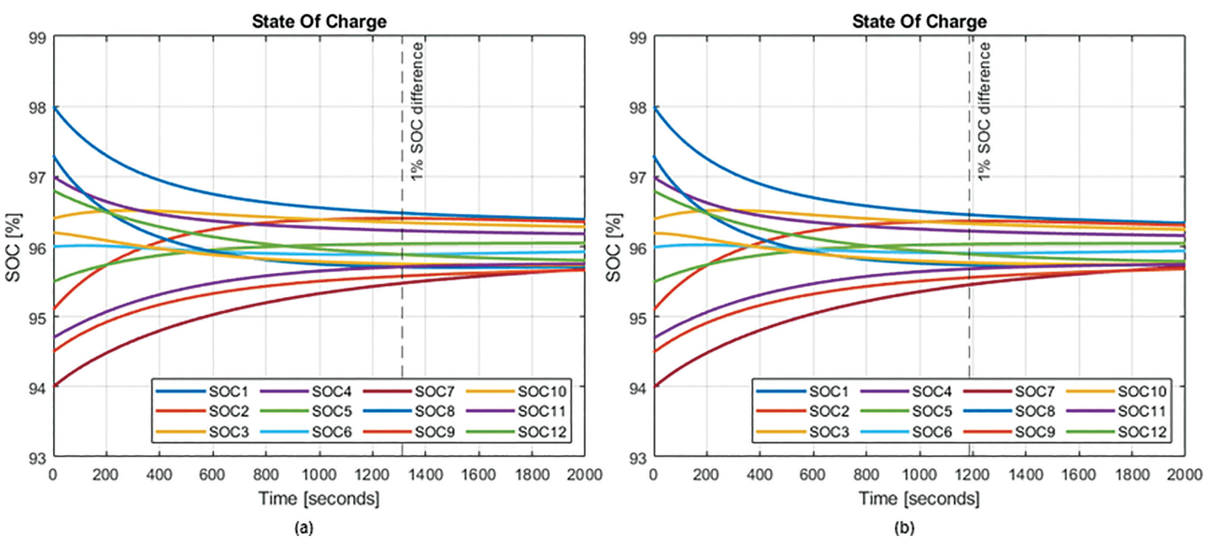

Figure 7. SOC progress during switched-capacitor balancing simulation (a), SOC progress during double-tiered switched-capacitor balancing simulation (b). SOC, state of charge.

switched-capacitor circuit. The difference in balancing time was 126 s, and the behaviour of the cells was quite similar.

4.4. Results with the double-tiered switched-capacitor with additional capacitor

Finally, we implemented an additional layer of capacitors into the MATLAB Simulink model, as depicted in Figure 6. This method of balancing was expected to be the fastest due to the presence of the additional capacitor connected to the battery pack. However, the simulation results (Figure 8) showed that with the capacitor value being the same as the others, it actually made the balancing slightly slower. The balancing time to achieve a one percentage point difference in SOC was 1195 s, which was 9 s slower than without the additional capacitor.

4.5. Final comparison of balancing with different topologies

Finally, we compared not only the results of the simulations at a one percentage point SOC difference but also at the end of the simulation time. These findings are presented in Table 2.

Table 2 displays the SOC differences at the end of each simulation. The first simulation using the switched-capacitor circuit achieved an SOC difference of 0.72 percentage points. The double-tiered switched-capacitor simulation resulted in an SOC difference of 0.D68 percentage points, while the third circuit with an additional capacitor achieved an SOC difference of 0.65 percentage points. These results indicate that the inclusion of an additional capacitor has the potential to expedite the balancing process. It is interesting to note that, although Cell number 7 initially had the lowest SOC and maintained this position at the one percentage point SOC difference, Cell number 9 exhibited the lowest SOC at the end of the simulation time in all cases.

4.6. Dynamic load battery pack balancing with improved simulation parameters, OCV curve modelling and cell impedance measurement

For the purpose of further research, the previous simulations and the battery pack have been slightly modified. To achieve higher precision, the simulations needed to be brought closer to a real battery pack. Therefore, the impedance on real cells was measured, and the measured values were used in the simulations. Cells from which a battery pack would be preferred to be assembled in the future were used. Similarly, the parameters in the Simscape model were adjusted to reflect the lithium iron phosphate (LFP) characteristics of the cell. The LFP technology was chosen due to its higher safety for the future construction of the battery pack and balancer. Cells from the Lithium Werks manufacturer’s 18650 series, specifically the APR18650M1B model (Lithium Werks Inc., 2019), were selected. These are the cells available for future needs. The catalogue parameters of the cell and simulations are provided in Table 3. The capacity of the cells was set to 1.1 Ah in the simulations, multiplied by a random value

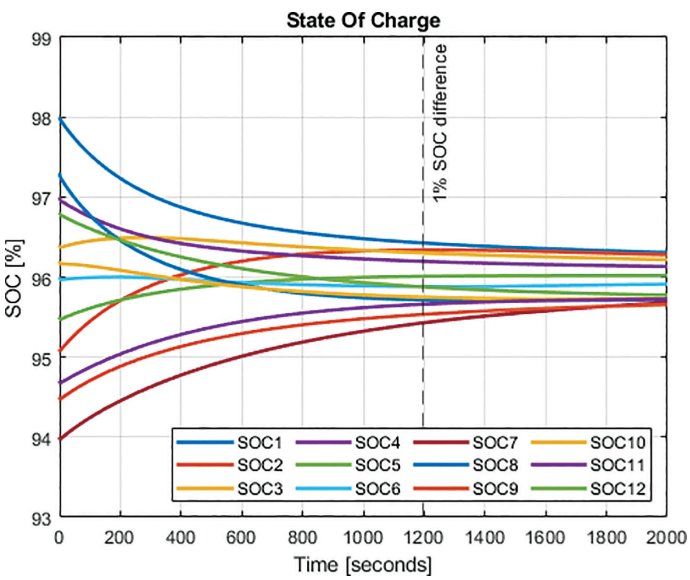

Figure 8. SOC progress during double-tiered switched-capacitor with additional capacitor balancing simulation. SOC, state of charge.

ranging from 98% to 100% for more realistic conditions. The switching frequency is chosen to be 1 kHz because the Nyquist plot of the battery cell shows the lowest resistance at this frequency (Fernández Pulido et al., 2017).

The simulations were expanded to include dynamic loading of the battery pack. This involves discharging, idle time and subsequent charging. In all three of these phases, the SOC of the individual cells is balanced. Based on the previous results of the simulations, the double-tiered switched-capacitors circuit was selected for further simulations and for the construction of the balancer.

The discharge characteristic of the cell is determined by the OCV curve. To closely approximate the real values of the APR18650M1B cell, the model parameters were adjusted to align as closely as possible with the catalogue data. According to the catalogue, the minimum voltage on the cell is 2 V, and the maximum for charging cutoff is 3.6 V. The slope of the curve in the linear region was set according to the corresponding curve in the catalogue (Lithium Werks Inc., 2019). The exponential region in the model begins at 3.28 V with a value of 0.04 Ah. The used OCV curve is directly plotted from the Simscape model in Figure 9.

Table 3. Parameters of the used battery cell and simulation parameters for dynamic double-tiered switched-capacitor balancing simulations.

Parameter	Value	Unit
Battery nominal voltage	3.3	V
Battery capacity	1.1	Ah
Battery response time	5	s
Battery internal resistance	12.6	mΩ
Capacitor capacitance	4.7	mF
Switching frequency	1	kHz
Simulation time	4,000	s

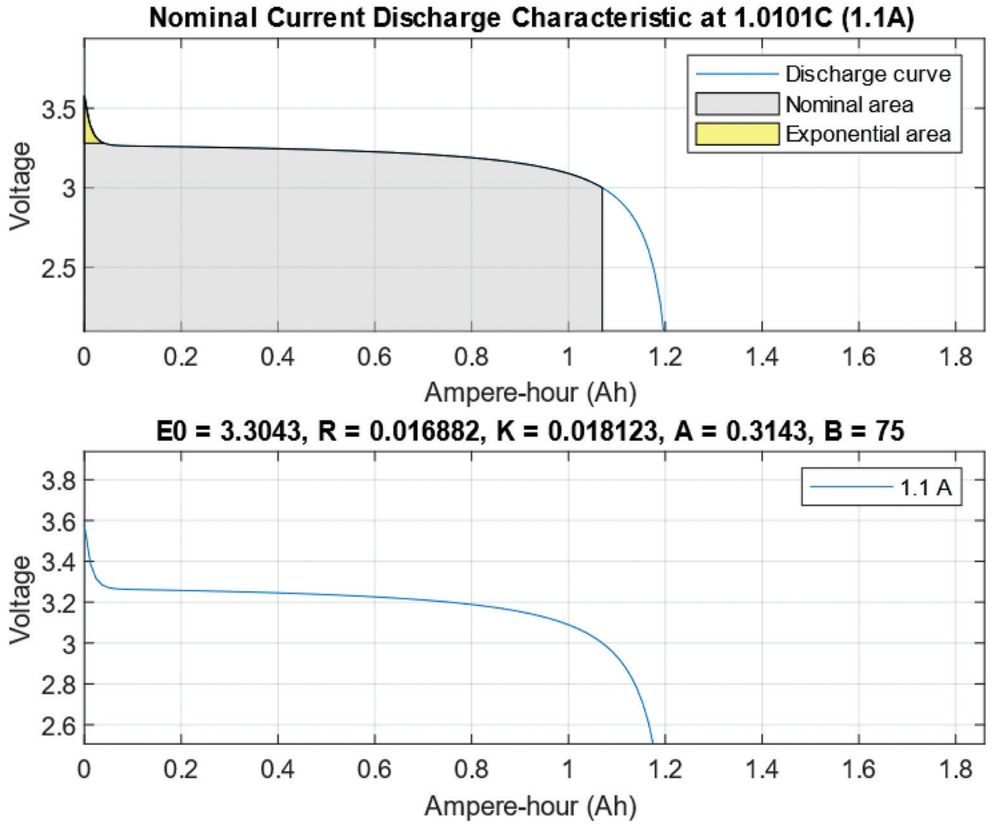

Figure 9. The OCV curve used for the Simscape model of the LFP Li-ion battery cell APR18650M1B. LFP, lithium iron phosphate; OCV, open-circuit voltage.

Table 4. Resistance measurement of Lithium Werks APR18650M1B cells and final calculation.

Cell number	Measurement 1 (mΩ)	Measurement 2 (mΩ)	Measurement 3 (mΩ)	Average (mΩ)	Final resistance (mΩ)
1	19,444	19,743	2,046	19,882	16,882
2	19,231	21,296	2,085	20,459	17,459
3	19,825	19,823	2,105	20,233	17,233
4	19,738	20,305	2,162	20,554	17,554
5	20,674	20,732	2,249	21,299	18,299
6	21,000	20,129	2,242	21,183	18,183

In order to achieve the most accurate results in simulations with dynamic loading, the impedance of six cells was measured. Real cells in the battery pack do not possess identical, ideal impedance values, and their voltage varies with different loads. This data was then utilised in the simulations, and various impedance values were randomly set from the measured set of values. The impedance was measured using a device GBM-3080 from GW Instek (Taipei, Taiwan). For precision in measurement, the cells were placed into a holder during the measurements, which were conducted three times. A value of 3 mΩ, representing the holder resistance, was subtracted from the measured data. The measured values are provided in Table 4. The measured data are approximately 5 mΩ higher compared to the catalogue value.

In the previous simulations, the battery pack operated solely, without any load or charging (Marcin et al., 2023). The simulation with dynamic loading is aimed at verifying the possibility of continuous balancing of the battery pack, as well as during discharge, idle state or charging. The initial SOC values of the cells were randomly selected from the range of 95% to 97% during one simulation and from 85% to 97% during the second. The simulation starts with a discharge current of 1.65 A, representing a value of 1.5 C. The battery module is loaded and charged with a current source. The discharge lasts for 1000 s, which should discharge the cells to approximately half of their SOC. This is followed by a 500 s pause, during which the battery pack neither charges nor discharges. Subsequently, at 1500 s, the pack begins charging. Full charge is aimed by using the CCCV method. Initially, the battery pack is charged at a current of 1 C, equivalent to 1.1 A. To precisely switch to the voltage source, the voltage of each cell is monitored. The program is designed so that if any cell reaches a voltage of 3.6 V, it triggers the switch. This value represents the catalogue value for disconnecting the cell from the current source. The circuit switches from the current source to the voltage source with a value of 43.2 V, representing 12 times the maximum voltage of the cell. Both the current and voltage sources, as well as switches, are simulated using elements from the Simscape environment. An ideal switch is used for switching purposes.

4.7. Results with dynamic load battery pack balancing simulations

The results of the first set of initial parameters, where the SOC of the cells was randomly selected from the range of 95% to 97%, are depicted in Figure 10 (a). Balancing occurs in all three states of the simulation, but it is not that obvious due to the small differences in SOC. During charging or discharging, balancing occurs more slowly than in the idle state. Due to the small SOC difference between the cells, the balancing process is relatively slow. Therefore, the same model was subsequently simulated with different initial values.

The current and voltage profiles of the battery pack during simulations with the initial SOC in the range of 95%–97% are plotted in Figure 11 (a). The current was kept constant until switching to charging by constant voltage. At this point, a minor current and voltage spike were observed. The voltage remains constant during the idle state. During charging and discharging, it varies depending on the cell model.

In the results of the second set of the initial values, we observe more significant differences in cell balancing, as depicted in Figure 10 (b). Initially, the gap between the minimum and the maximum SOC of the cells is twelve percentage points. Towards the end of charging, when switching to constant voltage charging, this gap decreases to only five percentage points. In the previous parameters, the initial gap was two percentage points, and it remained approximately the same before the end of charging when switching to constant voltage charging. Since for LFP cells, with a two percentage point SOC difference, the voltage difference between cells is minimal, the balancing speed is also minimal. However, once we increased the SOC difference, the voltage deviation also increased, thereby accelerating the speed of balancing. This assertion is supported by the results shown in Figure 10 (b).

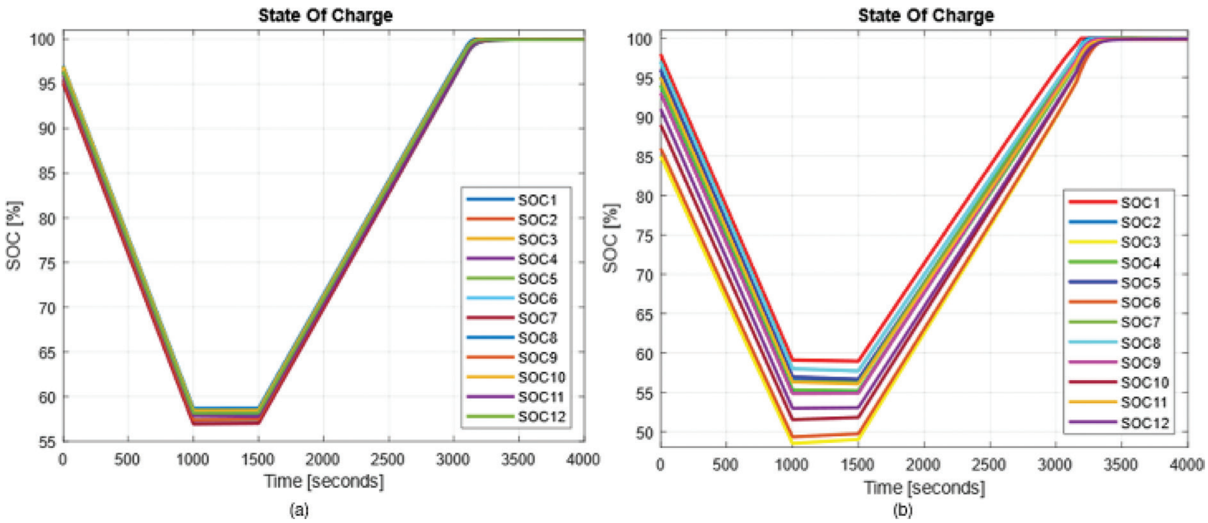

Figure 10. The SOC of the 12S LFP battery pack with double-tiered switched-capacitor balancing with the initial SOC in the range of 95%–97% (a), the SOC of 12S LFP battery pack with double-tiered switched-capacitor balancing with the initial SOC in the range of 85%–97% (b). LFP, lithium iron phosphate; SOC, state of charge.

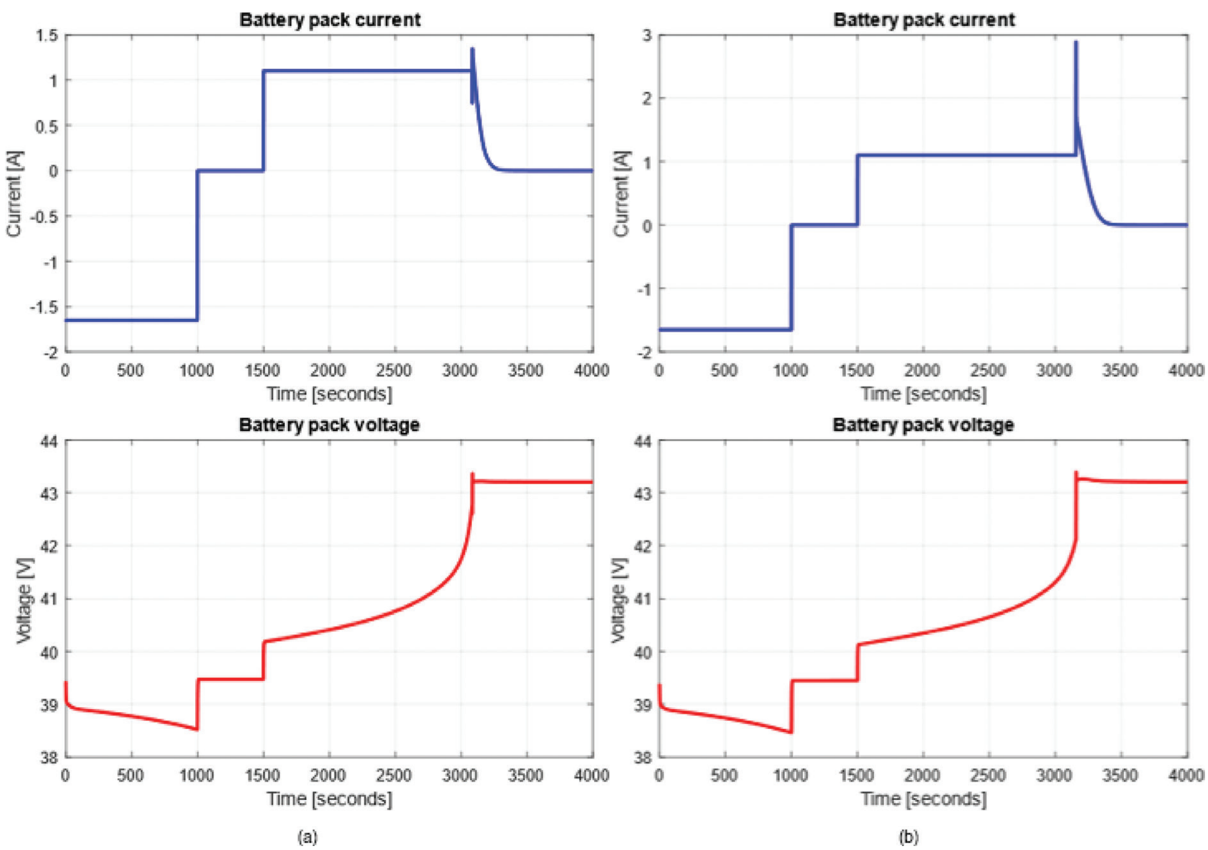

Figure 11. Voltage and current of the 12S LFP battery pack with double-tiered switched-capacitor balancing with initial SOC in the range of 95%–97% (a), voltage and current of the 12S LFP battery pack with double-tiered switched-capacitor balancing with initial SOC in the range of 95%–97% (b). LFP, lithium iron phosphate; SOC, state of charge.

The current and voltage profiles of the battery pack during simulations with an initial SOC in the range of 85%–97% are depicted in Figure 11 (b). These profiles resemble those in the previous case, but with one notable difference. The current spike during charging at the switch to constant voltage charging is significantly higher. This issue could arise from multiple causes or a combination of factors.

- The first and perhaps the most probable cause could be switching to constant voltage charging 'too early' during charging. In the simulation, we monitor a cell that reaches first a value of voltage 3.6 V. At that time, cells with a lower SOC have lower voltage.
- The second cause could be incorrect simulation settings. We are not familiar with the exact behaviour of the model used from the Simscape library. Therefore, the cell model may behave unpredictably.
- The third possibility could be the incorrect modelling of real current limiting. The source's ability to supply a higher current, which a real charger should be able to limit, might be the cause.

These causes may not imply anything serious and could just be transient events in the simulation. However, if they were to occur in a real balancer, they could lead to stress or overcharging of the cells. Similar transient events occur when there are current spikes at the moment the cells reach 100% SOC. In this case, again, there is a difference between less charged cells and those already at 100% SOC. Since they are connected to the same constant voltage source, the more charged cells are overcharged. These transient states will be the subject of further research.

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