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A COMPARATIVE ANALYSIS OF SINGLE SWITCHED CAPACITOR AND SWITCHED SHUNTING RESISTOR BATTERY CELL BALANCING METHODS

[1]Siaw, F.L.*, [2]Teow, M.Y.W., [1]Thio, T.H.G., [1]Wong, J.X.

[1] Centre for Advanced Electrical and Electronic Systems (CAEES), Faculty of Engineering, Built Environment and Information Technology, SEGi University, 47810 Petaling Jaya, Selangor, Malaysia.

[2] School of Engineering and Technology, PSB Academy, City Campus, Singapore.

* Corresponding Author: siawfeilu@segi.edu.my TEL: (603)-61451777

Abstract: Battery cell balancing holds significant importance in electric vehicles (EVs) due to its potential impact on cell imbalance. Battery packs containing multiple cells require continuous balancing to minimize variations between cells. However, over time and after multiple charge and discharge cycles, individual cells may exhibit varying state of charge (SOC). Battery cells within the same battery pack with different SOC values are at risk of overcharging or over-discharging, leading to a reduction in their useful lifespan. This paper presents a comparative analysis of the single switched capacitor (SSC) cell balancing method and the conventional switched shunting resistor (SSR) cell balancing method. Analysis is conducted through simulations of cell balancing models using MATLAB/Simulink. Simulation results show that the SSR cell balancing method achieved shorter balancing time, approximately one-quarter to one-third of the time needed by the SSC cell balancing method. On the other hand, the SSC cell balancing method demonstrated higher output power with an 8.32% higher SOC in case study 1 and 29.03% higher SOC in case study 2. Therefore, our findings favour the SSC method as it results in a higher final SOC after equalization.

Keywords: comparative analysis; state of charge; cell balancing; single switched capacitor; switched shunting resistor

1. Introduction

The growing demand for electric vehicles (EVs) in recent years calls for an enhanced lithium-ion battery management system to optimize vehicle performance. One of the factors affecting vehicle performance is battery cell imbalance, denoting capacity disparities among individual batteries within a battery pack, arising from manufacturing defects or performance variances over time (Daowd *et al.*, 2011; Yang & Siaw, 2021). Such disparities can lead to curtailed EV travel range and adverse consequences on the battery pack's lifecycle. To extend the lifetime of the battery pack, it is essential to routinely equalize the battery cells, thereby minimizing voltage differences between them (Torchio *et al.,* 2016).

A battery management system monitors and controls the charging of the battery pack. It tracks parameters such as system voltage, current, temperature, the state of charge (SOC) of individual battery cells, state of health, and remaining useful life (Bhagat *et al.*, 2022; Siaw *et al.*, 2021). A battery's SOC quantifies the amount of remaining available charge in relation to the battery's nominal capacity and is used to mitigate the risk of battery damage, ensure safety, as well as optimize charging efficiency. (Chen *et al.*, 2018; Nath & Rajpathak, 2022; Zhou *et al.*, 2021). An SOC value of 1 indicates a fully charged battery cell, while an SOC value of 0 signifies a fully discharged or empty cell. This is the lowest permissible voltage and is referred to as the cut-off voltage (Bruen *et al.*, 2015; Chandrakala, 2021).

Two distinct approaches exist for battery cell balancing, namely passive and active cell balancing, commonly referred to as dissipative and non-dissipative balancing, respectively (Babu & Ilango, 2022; Lee *et al.,* 2011). Passive cell balancing methods, such as fixed resistor method and switched shunting resistor (SSR) method, utilize the lowest-capacity cell in the battery pack as the reference point, enabling each battery cell to discharge through a parallel-connected resistor until equilibrium capacity is achieved (Paidi & Gudey, 2022; Samaddar *et al.*, 2020). The SSR method incorporates a switching resistor that routes excess charge from higher-charged cell to discharge through a resistor until the SOC matches with that of lower-charged cells in the battery pack (Song & Lee, 2023). This approach is widely used in applications with small cell variations and low power requirements. However, the cell balancing process generates heat through the dissipation of excess charge, resulting in elevated battery temperatures. This is undesirable because it reduces system efficiency due to energy loss in the form of heat. In addition, battery life is shortened due to continual heating (Katoch & Eswaramoorthy, 2020; Kumar *et al.*, 2023).

In the active cell balancing approach, excess energy from overcharged battery cells is efficiently redistributed to undercharged cells through energy transferring elements (Duraisamy & Kaliyaperumal, 2020; Wei *et al.*, 2018). Various topologies are available according to the active element used, such as capacitors, inductors, transformers, as well as energy convertors (Daowd *et al.*, 2012; Shah *et al.*, 2018). This method is also known as nonenergy-consumption balancing or lossless balancing. Active cell balancing methods have the capability to transfer surplus energy from an overcharged cell to the weakest cell within the pack, thereby equalizing the SOC of the cells (Chen *et al.*, 2022; Hoekstra *et al.*, 2022). Notably, this process minimizes heat dissipation, with the excess energy effectively redistributed to other battery cells. This approach enhances energy conservation in the battery pack by reducing thermal losses (Hemavathi, 2021; Nivya and Deepa, 2021).

Capacitor balancing is a widely adopted energy transfer method due to its attributes, including straightforward control, compact size, minimal stress on components, sensor-independence, and non-complex controllers (Alvarez-Diazcomas *et al.*, 2023). The single switched capacitor (SSC) balancing can be considered as a derivation of the switched capacitor method, utilizing only a single capacitor. In the case of SSC, the balance of *n* battery cells requires just one capacitor and *n*+5 semiconductor switches (Yildirim *et al.*, 2019). The SSC method employs an uncomplicated control strategy, wherein a controller identifies the higher and lower charged cell, along with the corresponding switches to facilitate the transfer of excess charge from the higher cell to the lower cell (Daowd *et al.*, 2014; Wang *et al.*, 2022).

This paper presents simulations of two cell balancing methods in MATLAB, followed by a comparative analysis of their balancing time and effectiveness. MATLAB/Simulink models for both the SSC cell balancing method and the conventional SSR cell balancing method were developed with identical initial SOC levels.

2. Materials and Methods

This section provides an overview of simulation work using MATLAB. The design was realized through the use of Simulink block modelling. The investigation focuses on the development of a battery pack with four lithium-ion batteries to facilitate the simulation of the cell balancing system. These lithium-ion batteries are interconnected in a series configuration. The activation of cell balancing algorithm occurs when the variance of SOC between batteries surpasses a threshold of 0.05%.

The system has the capability to measure the SOC of each individual battery cell within the battery pack. Furthermore, it identifies the battery cell with the lowest SOC and the one with the highest SOC in the pack. To achieve this, two circuit systems were developed: an SSR balancing system and an SSC cell balancing system.

2.1. Switched Shunting Resistor (SSR) Cell Balancing Method

The SSR cell balancing method was designed to efficiently equalize the charge distribution among battery cells. It achieves this by removing excess energy from highly charged cells through a resistor until the charge aligns with that of lower-charged cells or reaches a predetermined reference level (Daowd *et al.,* 2013). This method is based on regulating the energy in higher SOC battery cells by using an ideal switch and a variable resistor in MATLAB. When the system detects SOC imbalance in the battery cells, a MATLAB function is triggered to determine which switches to activate and which ones to keep open, thereby rebalancing the cells with higher, medium, and lower state of charge. **Figure 1** illustrates the flowchart of the SSR cell balancing method. This method was implemented within the Simulink environment using block diagrams from the Simulink library, as illustrated in **Figure 2**.

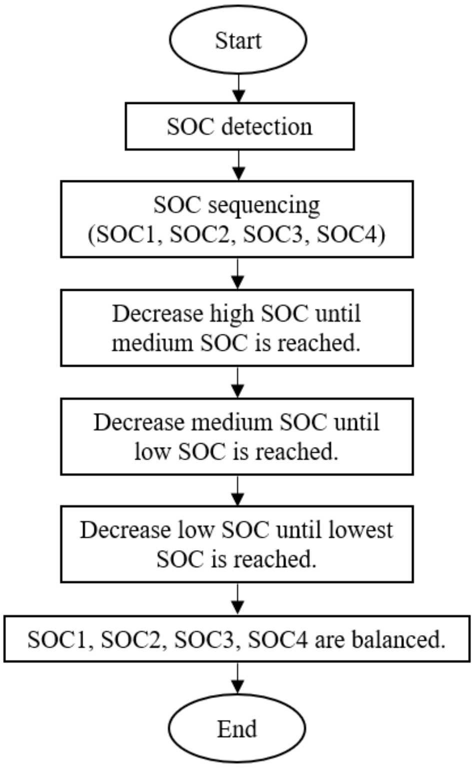

Figure 1. Overall workflow of the SSR method

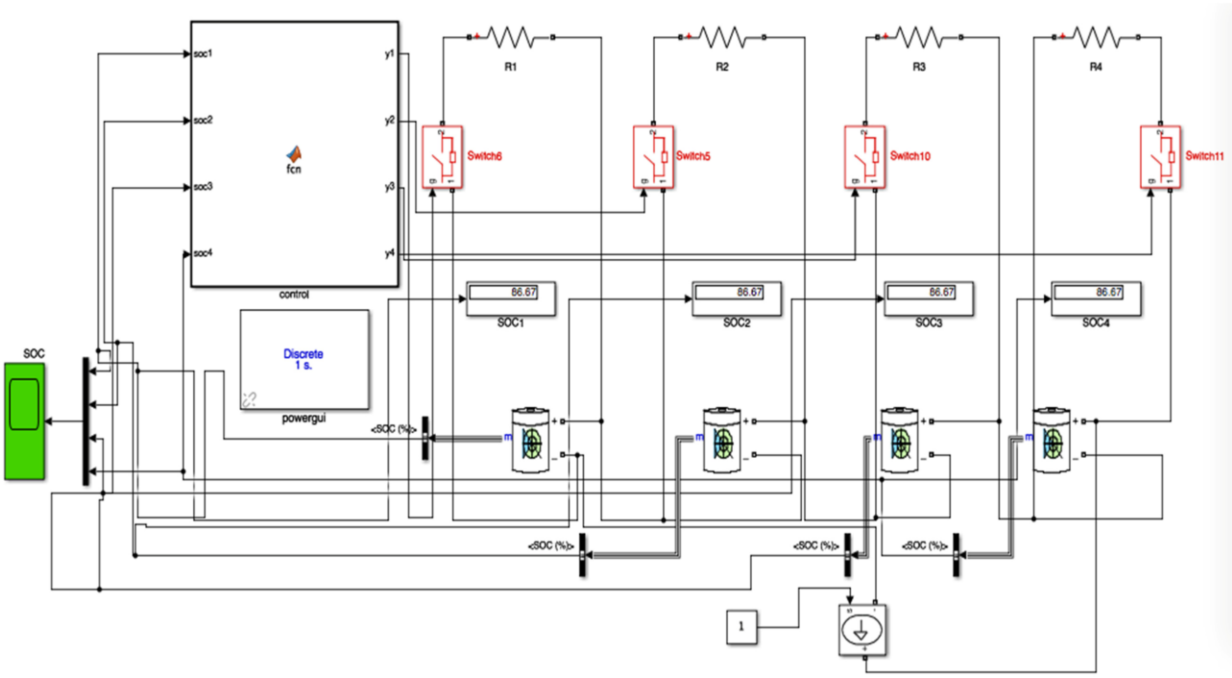

Figure 2. Simulink model of SSR cell balancing system

2.2. Single Switched Capacitor (SSC) Cell Balancing Method

The SSC cell balancing method is a derivation of the switched capacitor technique, requiring n+5 ideal switches to equalize n cells. The core concept involves an initial system assessment to identify the battery cell with the highest and lowest SOC. A MATLAB function controller was employed to control the corresponding ideal switches, facilitating the transfer of energy between different battery cells within the battery pack. **Table 1** provides a summary of SSC balancing system switches according to the number of battery cells. The workflow of SSC cell balancing method is presented in **Figure 3**. The construction of the SSC balancing model involves the utilization of nine ideal switches, a quantity derived from the parameter n+5, as indicated in the provided table. Given that the model incorporates $n = 4$ to represent four lithium-ion battery cells, the total number of ideal switches required is nine, as presented in **Figure 4**.

Table 1. SSC switches according to number of battery cells (Daowd *et al.*, 2013)

Number of Battery Cells (*n*)	**SSC Switches (*n*+5)**
2	7
3	8
4	9
5	10
6	11
8	13
16	21

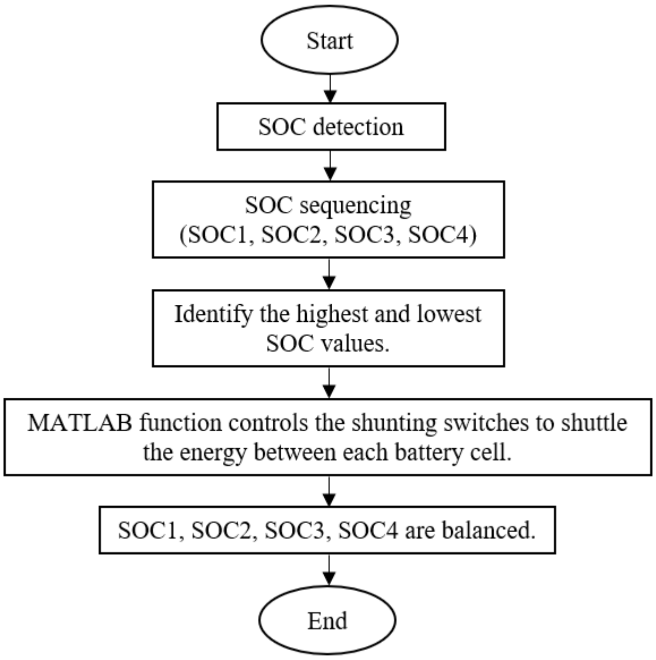

Figure 3. Overall workflow of the SSC method

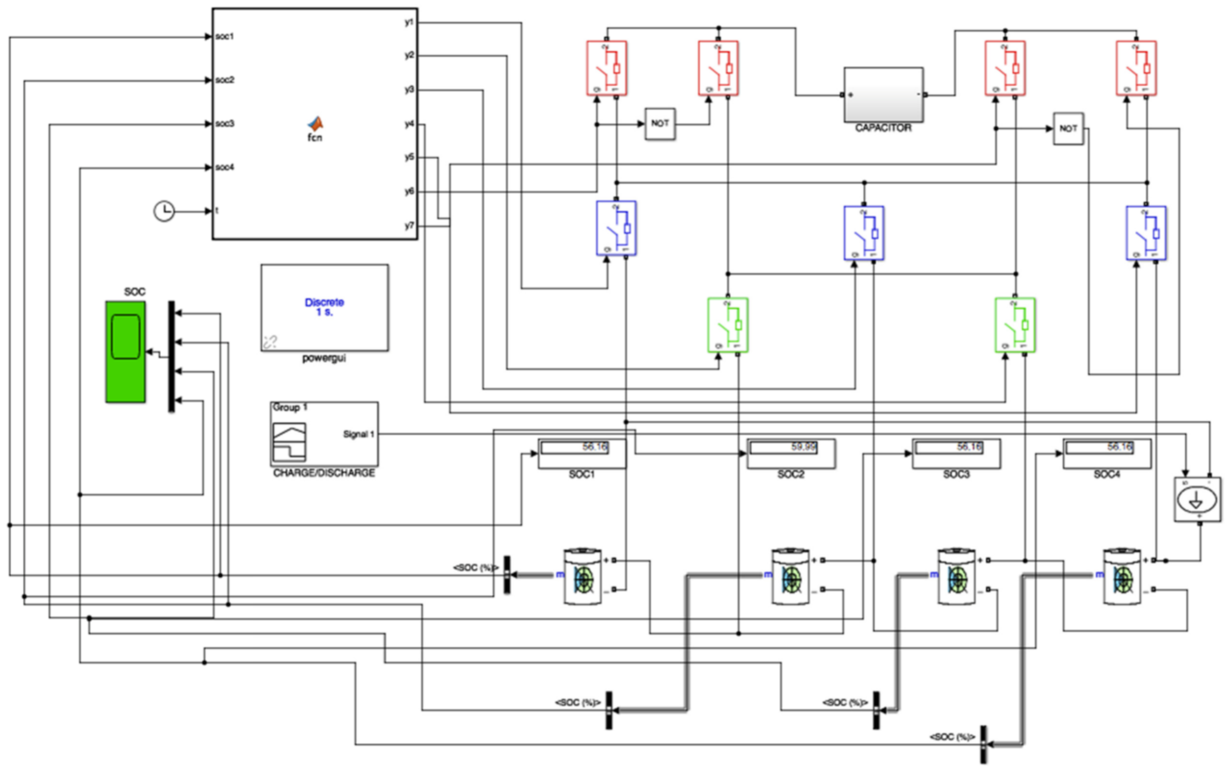

Figure 4. Simulink model of SSC cell balancing system

3. Results

This section presents a comparison of two case studies using pre-established cell balancing systems of four series-connected lithium-ion battery cells in MATLAB/Simulink (**Figure 2** and **Figure 4**). Each cell balancing system was simulated under identical SOC starting conditions. Simulation results collected from both balancing systems were used to generate the graphs. For this study, battery cell 4 was set with the highest SOC value while cell 1 was set with the lowest SOC value. Notably, battery cell 2 and battery cell 3 maintain fixed initial SOC values of 78% and 76%, respectively.

3.1. Case Study 1: SOC Difference of 6% between the Highest SOC Cell and the Lowest SOC Cell

The first simulation, designated as case study 1, adheres to the parameters outlined in a reference research paper, where the cell balancing system tries to balance an SOC difference of 6% (Daowd *et al.*, 2011). **Figure 5** illustrates a scenario with the initial state of a 6% difference in SOC between the highest cell and the lowest cell in the battery pack in the absence of any cell balancing. The state of charge for each cell was as follows: cell 1 (74%), cell 2 (78%), cell 3 (76%), and cell 4 (80%).

From simulation results, it was observed that the SSR cell balancing method successfully equalized four battery cells within the battery pack in approximately 33 minutes. **Figure 6** presents the final SOC values of each battery within the battery pack once the cell balancing process has completed. On the other hand, the SSC cell balancing method successfully equalised the SOC among four battery cells within the battery pack in approximately 156 minutes or 2.6 hours. **Figure 7** shows the final SOC of the batteries within the battery pack following the completion of the cell balancing process.

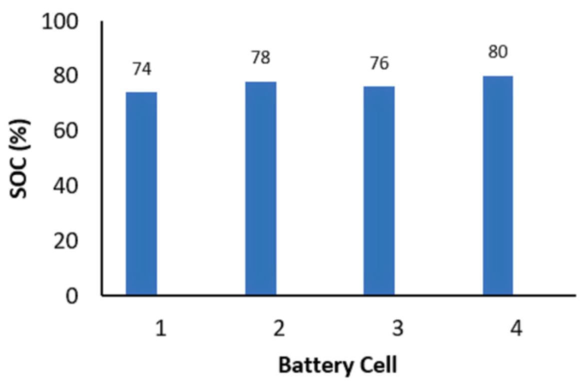

Figure 5. Initial SOC values before cell balancing for case study 1

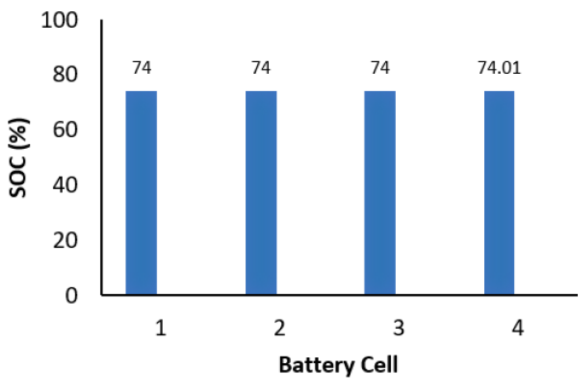

Figure 6. Final SOC values after SSR balancing for case study 1

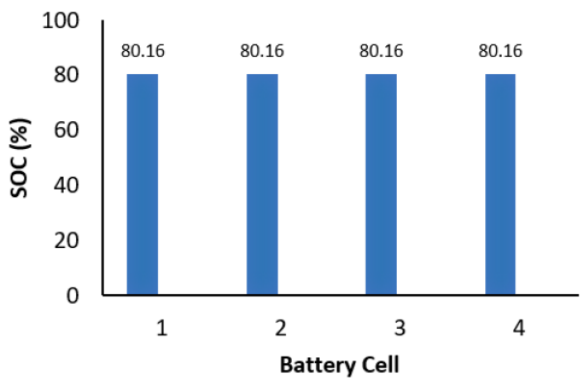

Figure 7. Final SOC values after SSC balancing for case study 1

3.2. Case Study 2: SOC Difference of 18% between the Highest SOC Cell and the Lowest SOC Cell

For case study 2, the percentage difference in SOC between the highest SOC cell and the lowest SOC cell is increased to 18%. **Figure 8** presents the initial SOC values with 18% difference between the highest and lowest cell within the battery pack. The SOC values for each cell were as follows: cell 1 (62%), cell 2 (78%), cell 3 (76%), and cell 4 (80%).

From simulation results, the SSR cell balancing method successfully achieved SOC equalization among four lithium-ion battery cells in approximately 133 minutes or 2.2 hours. **Figure 9** presents the final SOC values of each battery within the battery pack after cell balancing process was completed. On the other hand, the SSC cell balancing method effectively balanced the SOC among four lithium-ion battery cells in approximately 390 minutes or 6.5 hours. **Figure 10** depicts final SOC values of each battery within the battery pack after cell balancing was accomplished. **Table 2** presents a comparative analysis of the results obtained from SSR and SSC cell balancing methods.

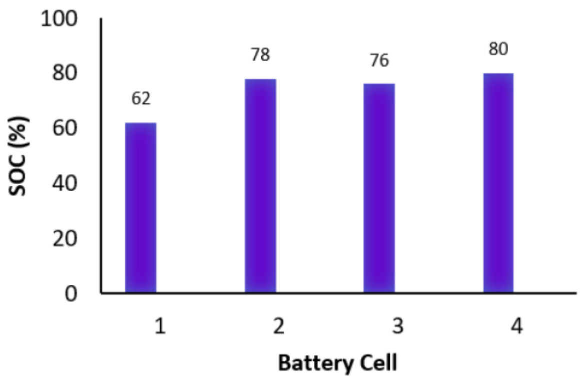

Figure 8. Initial SOC values before cell balancing for case study 2

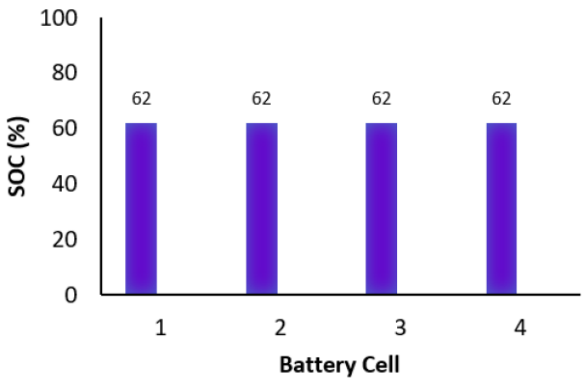

Figure 9. Final SOC values after SSR balancing for case study 2

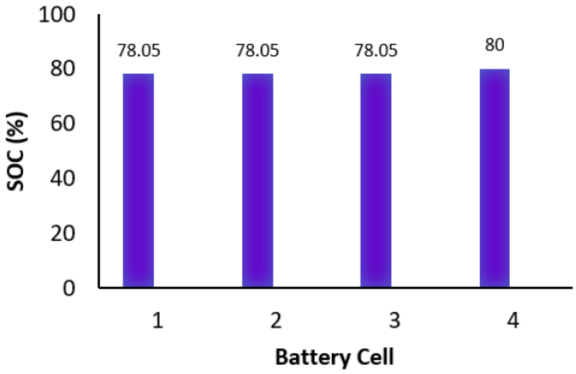

Figure 10. Final SOC values after SSC balancing for case study 2

Table 2. Results of SSR and SSC balancing methods for four series-connected battery cells

Case Study	SSR Simulation Results		SSC Simulation Results	
	Final SOC (%)	Balancing Time (minutes)	Final SOC (%)	Balancing Time (minutes)
1	74-74.01	33	80.16	156
2	62	113	78-80	390

4. Discussion

Table 2 presents a comparative analysis of two cell balancing methods, SSR and SSC, applied to a series-connected configuration of four battery cells. The table provides a summary of final SOC values and the corresponding balancing times for each case study. In the first case study, SSR simulation results showed final SOC values ranging from 74% to 74.1% and required 33 minutes to balance. In contrast, SSC simulation results achieved a higher SOC value of 80.16%, albeit with a longer balancing time of 156 minutes. In the second case study, SSR simulations achieved an SOC value of 62% and needed 113 minutes to balance. On the other hand, SSC simulations achieved SOC values in the range of 78%-80%, taking 390 minutes to balance.

Analysis of the results in **Table 2** reveals significant disparities in balancing time between the SSR method and the SSC method. While the SSC method demonstrates effective balancing with minimal power losses and higher SOC values, it comes with the drawback of longer equalization time. On the other hand, the SSR cell balancing method exhibits a shorter balancing time than the SSC method, but it incurred higher power losses during the balancing in comparison to the SSC cell balancing method.

The longer balancing time observed in the SSC cell balancing method compared to the SSR cell balancing method can be attributed to operational differences between the two techniques. Firstly, SSC balancing method relies on the controlled transfer of charge using a capacitor. This involves charging and discharging the capacitor to redistribute energy among the battery cells, a process that can be inherently slower due to the limitations of capacitor discharge rates. The second technique which is the SSR method, involves shunting resistors that can dissipate energy rapidly, allowing for faster balancing of cell SOC. When a battery cell's voltage exceeds a certain threshold, the shunting resistor provides a low-resistance path for current to flow, enabling quicker voltage equalization. This approach minimizes the time required to bring all battery cells to a balanced SOC level.

Analysis of simulation results reveals a significant contrast between the two cell balancing techniques. The SSR cell balancing method demonstrates a shorter balancing time, approximately one-fourth to one-third of the duration required by the SSC cell balancing method. However, the SSC approach yields higher output power, with case study 1 showing an 8.32% increase in SOC and case study 2 achieving 29.03% higher SOC value. Therefore, the SSC cell balancing method is preferred, as it achieves higher equalized SOC levels, which will positively contribute to the overall performance of EVs. These results provide valuable insights into the trade-offs power loss and balancing time for these two methods in a series-connected battery cell setup, offering essential information for the design and optimization of battery management systems in practical applications.

5. Conclusion

This paper provides simulations results to evaluate the performance and limitation of both active and passive cell-balancing methods. The study focuses on two distinct approaches: the SSR cell balancing method and the SSC cell balancing method. The simulations for both methods are carried out in MATLAB/Simulink, where cell balancing models are developed. Simulations are collected from two case studies with SOC differences of 6% and 18%. The aim of this research is to determine the method that can achieve better cell balancing while minimizing balancing time. Simulation results indicate that the SSC cell balancing method exhibits lower power losses after completing the balancing process. However, it does require more time for equalization. On the other hand, the SSR cell balancing method demonstrated faster balancing time with lower final SOC values. The lower final SOC values suggest that this approach results in increased power losses. Nevertheless, it accomplished equalization in less than half the time compared to the SSC cell balancing method. In summary, the longer balancing time in the SSC cell battery cell balancing method, as compared to the SSR cell balancing method, can be attributed to the inherent characteristics of capacitors, which may limit discharge rates, and adds complexity of controlling the charge transfer process. The SSR method, on the other hand, offers a more direct and rapid approach to balance cell voltages, resulting in shorter balancing times. These findings show the importance of considering the operational characteristics of different balancing techniques when selecting the most suitable method for a given battery cell configuration.

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Credit Author Statement

Conceptualization and methodology, Siaw, F.L., Teow, M.Y.W., and Thio, T.H.G.; software and validation, Wong, J.X., formal analysis, Siaw, F.L.; investigation, Wong, J.X.; resources, Thio, T.H.G.; data curation, Siaw, F.L. and Thio, T.H.G.; writing—original draft preparation, Siaw, F.L., Thio, T.H.G., Teow, M.Y.W. and Wong, J.X.; writing—review and editing, Teow, M.Y.W.; visualization, Teow, M.Y.W.; supervision and project administration, Siaw, F.L.

Conflicts of Interest

The authors declare no conflict of interest.

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