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Active Cell Balancing Design for Battery Management Systems

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Abstract:

The increasing demand for higher energy storage capacity in electric vehicles (EVs) has necessitated the development of more efficient battery management systems (BMS) to extend battery life. This study proposes an inductor-based active cell balancing method to eliminate state-of-charge (SoC) imbalance in lithium-ion (Li-ion) battery packs. An inductive active cell balancing system is designed and analyzed for Li-ion batteries to achieve SoC equalization across battery cells, extending battery lifespan while minimizing energy losses. Active balancing outperforms passive methods with faster operation and higher efficiency, ideal for power-intensive applications. The designed model undergoes extensive simulations performed in the MATLAB/Simulink environment verify the effectiveness of the system in terms of balancing time, energy transfer efficiency and applicability. The single inductor-based structure reduces circuit complexity and component cost, increasing the practical use of the system. The findings contribute to the advancement of battery management systems, making energy storage solutions more reliable and effective.

Key words: Active Cell Balancing, Inductor-Based Balancing, SoC, BMS, Electric Vehicle Batteries

1. INTRODUCTION

The transition to electrical energy has become increasingly important, particularly in the transportation and industrial sectors. In this context, battery technology plays a critical role in various applications. For many years, batteries have served as the primary energy storage solution for electric land vehicles. Additionally, they are widely used in communication devices, wireless hand tools, and other portable technologies. The depletion of petroleum resources and the rising demand for energy have accelerated the adoption of EV and energy storage systems in residential applications. Technological advances have led to the development of home batteries and energy storage solutions, enhancing energy efficiency and safety.

To optimize the economic and operational efficiency of energy storage systems, it is essential to monitor key battery parameters such as the SoC, state of health (SoH), temperature, current flow, and the charge/discharge process. These factors directly influence battery performance and longevity. A long-lasting battery enables extended operation and improved energy efficiency [1], [2]. To maximize the lifespan of battery cells and minimize costs, it is crucial to monitor and regulate their technical specifications. Li-ion batteries are particularly sensitive to overcharging and deep discharging. Operating these cells outside their safe working range can result in battery damage, reduced lifespan, and potential safety hazards.

Battery packs are composed of multiple cells connected in series and parallel configurations to meet the voltage and power requirements of a given system. However, due to variations in operating conditions and

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uneven load distribution, the cells within a battery pack may reach different voltage or charge levels. If an effective cell balancing method is not implemented, the charge and discharge processes may cause SoC imbalances among the cells. The voltage and capacity differences between connected battery cells hinder the efficient operation of the battery pack [3]. Repeated charge/discharge cycles, manufacturing tolerances, aging, asymmetric degradation, and uneven temperature distribution contribute to inevitable variations in the chemical and electrical properties of battery cells.

To prevent safety risks, Li-ion batteries must be protected against overcharging, as excessive charging can lead to fire or explosion hazards [4]. Similarly, low-voltage protection is essential, as deep discharge can degrade battery properties. A safe operating range must be maintained to prevent overcharged or deeply discharged cells. The overall charging and discharging process of a battery pack is constrained by the most charged or least charged cell within the system. This limitation reduces the usable capacity of the battery, leading to premature charge/discharge termination and increased cycling, ultimately shortening battery life [5], [6], [7].

Cell balancing is a technique that ensures voltage equalization among battery cells. After balancing, all cells in the battery pack achieve nearly the same SoC. As illustrated in Figure 1, there are two primary cell balancing methods: passive and active cell balancing. Passive cell balancing, the simpler approach, is implemented using resistive elements [8], [9]. This method involves a parallel resistor and switch for each cell. During the balancing process, excess energy from overcharged cells is dissipated as heat through discharge resistors.

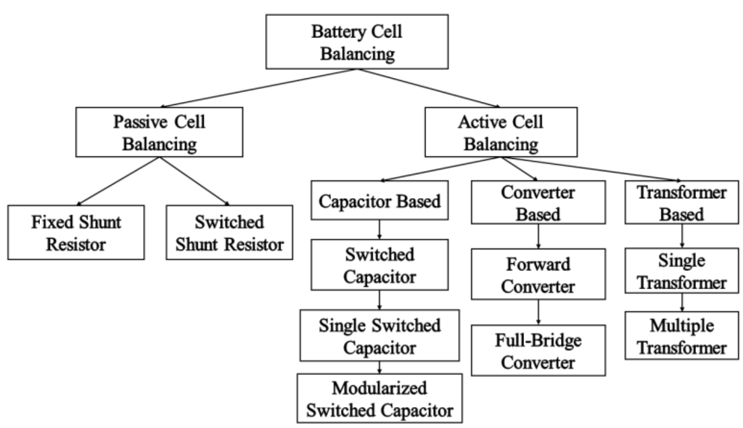

Figure 1. Battery cell balancing methods

The passive balancing method is cost-effective, compact, easy to implement, and requires minimal control. In contrast, active cell balancing transfers energy from higher-charged cells to lower-charged ones to mitigate energy imbalances within the battery pack. This technique improves energy utilization and extends battery life by minimizing unnecessary energy dissipation. Proper implementation of cell balancing methods

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enhances the efficiency and longevity of Li-ion battery systems, making them more suitable for applications requiring reliable and long-lasting energy storage.

In this study, the design of the inductor-based active cell balancing system for electric vehicles was examined. Li-ion batteries have a wide range of applications due to their high energy density and long life. However, charge imbalances between cells can negatively affect the performance and life of the battery; therefore, these imbalances are corrected by energy transfer between cells using active cell balancing methods. The performance of the system was evaluated with simulations performed in MATLAB/Simulink. In the recommended method, a single inductor was used to ensure energy transfer between the cells. Simulation results, balancing time, efficiency and applicability were evaluated, and the effectiveness of the method has been shown.

1.1 Passive Balancing

One of the primary methods for equalizing the charge distribution among battery cells is passive balancing. Passive balancing achieves cell voltage equalization by regulating the SoC through energy dissipation across resistors. In this approach, excess energy is dissipated as heat through resistors. It is widely used in lead-acid, nickel-based, and Li – ion batteries due to its simplicity and low cost. However, this method is inefficient because the continuous energy loss reduces overall battery lifespan [10]. The process operates through a control mechanism that measures the voltage of individual battery cells and discharges excess energy from cells with a high SoC using resistors. Passive balancing consists of two main stages: a continuous phase that manages energy distribution and a monitoring phase that detects voltage imbalances [11]. Although passive balancing has a simpler structure compared to active balancing, its significant energy loss makes it less efficient. Therefore, it is commonly used in small-scale portable electronic devices such as smartphones, laptops, and tablets. Passive and active balancing techniques are evaluated based on factors such as balancing speed, cost, system complexity, physical size, and energy efficiency.

1.2 Active Balancing

Energy transfers, repeated at high rates per second, retain the characteristic properties of the current and voltage trajectories, only varying depending on the voltages of the battery cells. The distribution of energy between the cells is shaped according to the interconnection structure of the active balancing methods [12]. Active balancing has been developed to overcome the limitations of passive balancing. This method, capacitors, transformers, converters, and inductors are used instead of resistors to provide energy transfer between battery the cells. Energy transfer between cells takes place from those with higher energy levels to those with lower levels, thus achieving balancing while preventing energy loss. It can be integrated into different technologies, regardless of the chemical properties of the battery cells. Although fast balancing and productivity are the important advantages, cost and structural complexity stands out as a disadvantage. The capacitor - based cell balancing method works with energy transfer between cells. However, this approach has disadvantages such as low speed and energy loss. Balancing using inductors or transformers offers a fast process, furthermore, challenges such as high cost and the need for additional filtering may be encountered [13], [14], [15].

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2. SOC ESTIMATION WITH SINGLE INDUCTOR ACTIVE BALANCING

Traditional inductor-based balancing methods involve sequential energy transfer between cells, leading to prolonged balancing times. In this study, an alternative cell balancing mechanism has been developed with less switches and inductors compared to existing inductor-based methods [16], [17], [18]. Li - ion battery system n series connected cells to optimize the energy distribution of the inductor aided active balancing method was applied. The proposed method aims to optimize energy distribution using a simplified circuit design, thereby minimizing power losses and enhancing overall system performance. As shown in Figure 2, the system utilizes a single inductor, along with twelve ideal switch elements (S_1-S_{n+1}) and diodes (D_1-D_{n+1}). The primary goal of this active balancing system is to efficiently redistribute energy between interconnected Li - ion cells (B_1 - B_N), transferring charge from cells with higher SoC to those with lower SoC. By employing a single inductor, the design is notably simplified compared to conventional multi-inductor approaches, making it more practical for large-scale battery applications. The use of less switching elements and the preference of the inductor -based method enables design to become simpler than traditional balancing approaches, while providing a more effective and applicable solution for large - scale battery systems. This method optimizes individual cell conditions and energy flow according to SoC differences.

2.1 Charging Phase

Throughout the charging phase, the inductor (L) functions as an intermediate energy storage element, temporarily accumulating excess energy from a high SoC battery cell before redistribution. When the control system detects a significant SoC difference, a corresponding MOSFET switch (S_1, S_2, …, S_n) is activated, allowing current to flow from the higher – SoC batteries (B_1, B_2, …, B_n) through the diodes (D_1, D_2, …, D_n) and into the inductor. As a result, magnetic energy accumulates in L_1, following Faraday's Law of Introduction. The control algorithm dynamically selects which battery to discharge based on the real-time voltage and current feedback from the BMS. The charging phase plays a crucial role in balancing the charge across the battery pack by ensuring that excess energy from higher-SoC cells is effectively stored in the inductor without significant losses.

Additionally, the efficiency of this energy storage process is dependent on multiple factors, including inductor selection, switching frequency, and circuit resistance. The inductor's value is chosen to optimize energy transfer while minimizing core losses and electromagnetic interference. Moreover, the PWM control scheme dynamically adjusts the duty cycle to regulate current flow, ensuring precise control over inductor charging. This phase is instrumental in preparing the energy for subsequent redistribution, which is essential for maintaining cell voltage uniformity and prolonging battery life.

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2.2 Discharging Phase

Upon reaching the required energy level, the inductor releases the stored energy to a lower-SoC battery cell. This is achieved by switching off the previously activated MOSFET and enabling the switches (S_{n+1}) that connects L to the target low-SoC cell (B_n). The energy transfer is facilitated through electromagnetic induction, ensuring a controlled and efficient redistribution process. The diodes function as current flow regulators, preventing reverse current and minimizing switching losses.

The efficiency of the discharging phase directly impacts balancing speed and overall system performance, as the rate of energy redistribution determines how quickly the battery cells reach equilibrium. A proportional-integral (PI) controller continuously monitors voltage levels and dynamically adjusts switching times to optimize charge transfer while preventing overcharging. Additionally, diodes play a crucial role in blocking unwanted backflow currents, mitigating unnecessary energy dissipation, and enhancing circuit stability.

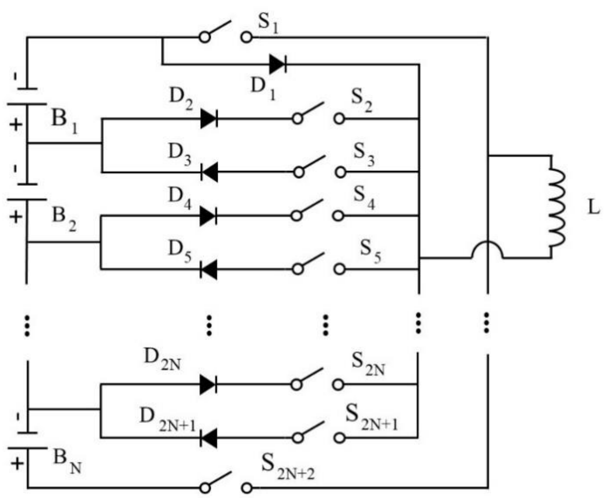

Figure 2. Active balancing circuit diagram

This active balancing technique effectively addresses cell-to-cell SoC inconsistencies in large-scale battery systems, including those used in EVs, renewable energy storage, and industrial applications. The use of a single inductor for charge transfer reduces component count, decreases overall weight, and enhances scalability. Future improvements could involve adaptive control algorithms that dynamically adjust energy transfer rates based on real-time operating conditions and battery aging effects, further improving efficiency and reliability [19]. Especially after the voltage difference between neighbouring cells is determined, a PWM signal is applied to the primary switching of the cell with higher voltage.The main disadvantage of this method is the extended energy transfer time from the first to the last cell as the battery sequence length increases. Nonetheless, the single inductor structure can perform a shorter balancing process in a shorter time compared to multiple inductor topology.

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This innovative method aims to extend the battery pack life, reduce energy losses, and optimize energy management in applications that require high power such as electric vehicles. In addition, with low switch loss losses and optimized inductor use, the system provides a more practical and sustainable solution compared to traditional passive and active balancing methods [20], [21], [22]. The imbalances between the cells are rapidly corrected and the overall performance and life of the battery are increased. On the other hand, the operating principle of the system is dynamically adjusted based on real -time feedback from BMS and energy losses are effectively minimized.

The use of a single inductor provides a cost advantage by occupying less space and makes the system more compact. Such balancing is particularly ideal for applications with limited space and high-power demand. However, the efficiency of the single inductor structure may remain limited in cases where the differences between SoC cells are large, because more energy transfer between the cells may lose loss when necessary. In addition, the correct selection and placement of diodes or switching elements is among the critical factors that affect the efficiency of the system.

3. Simulation and Results Analysis

This section evaluates the performance of the proposed single-inductor-based active balancing system through MATLAB/Simulink simulations. The system consists of four Li-ion cells, and its balancing mechanism redistributes energy to reduce SoC differences until equilibrium is reached. The circuit uses ten MOSFET switches (0.001 Ω internal resistance), a single inductor (L = 10,000 μH), and nine diodes (0.001 Ω resistance, 0.8 V forward voltage).

Table 1. Simulation parameters

PARAMETER	**VALUE**
Cell number (N)	4
Cell nominal voltage	3.7 V
Cell capacity	5 Ah
Inductor inductance	10,000 μH
Diode resistance	0.001 Ω
Switch resistance	0.001 Ω
Time step	0.0001 s
Charging rate	1 C
Discharging rate	1 C
Simulation duration	300 s

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Table 1 summarizes the key components used in the simulation, including the number of cells, inductance, and resistance values. Accurate specification of these parameters is essential for modeling the circuit's operating conditions, analyzing the battery cell balancing process, and evaluating system performance. The precise determination of these values enhances simulation accuracy and ensures that the results align with real-world operating conditions. This level of accuracy is essential for validating the simulation results against empirical data, allowing for more effective performance evaluations, improved predictive capabilities, and a deeper understanding of the system's behavior under varying operational parameters. The primary goal is to assess the effectiveness of the active balancing method in achieving SoC equalization while minimizing power losses [23].

Table 2. Initial SoC values for different battery operation scenarios

Battery No	Initial SoC in steady state	Initial SoC in charging	Initial SoC in discharging
1	84%	99%	51%
2	85%	98%	52%
3	81%	97%	53%
4	82%	96%	54%

Table 2 presents the initial SoC values for each unbalanced battery cell under different operating scenarios. Simulation results indicate that the initial SoC values of the battery cells are approximately 0.5 % higher than the predefined set points. This discrepancy arises from modelling accuracy, open-circuit voltage (OCV)-based SoC estimation, and numerical solver approaches. While the OCV-SoC relationship may introduce minor variations in initial conditions [24], solver sensitivity and iterative calculations can further contribute to deviations. Although these differences do not significantly impact overall accuracy, they can be minimized through improved parameter calibration and optimized model initialization techniques.

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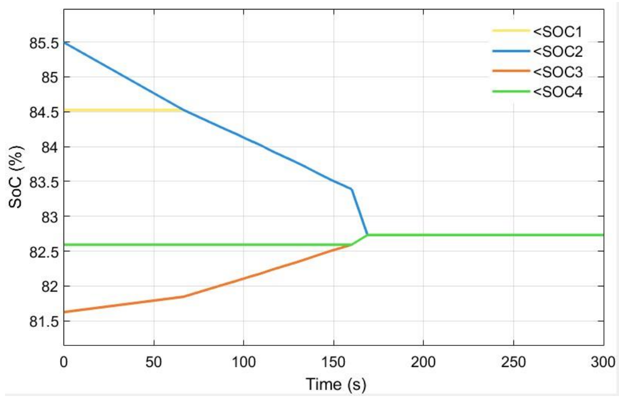

Figure 3. Steady-state simulation result

A logic-based control strategy dynamically regulates switching actions to optimize energy redistribution among cells. This mechanism generates PWM signals via two PWM generator blocks, adjusting switch operations in real time based on SoC measurements. The system response, including SoC equalization, energy transfer efficiency, and balancing time, is monitored through scope blocks. Figure 3 illustrates SoC variation during the balancing process. As the system operates, cells with higher initial SoC values discharge by transferring energy, while the cell with the lowest SoC accumulates charge. The convergence of SoC curves, occurring at approximately 160 seconds, confirms the successful completion of the balancing process and the effectiveness of the proposed method. The results further demonstrate that utilizing 10 switches and a single inductor enables efficient charge redistribution, minimizing SoC disparities.

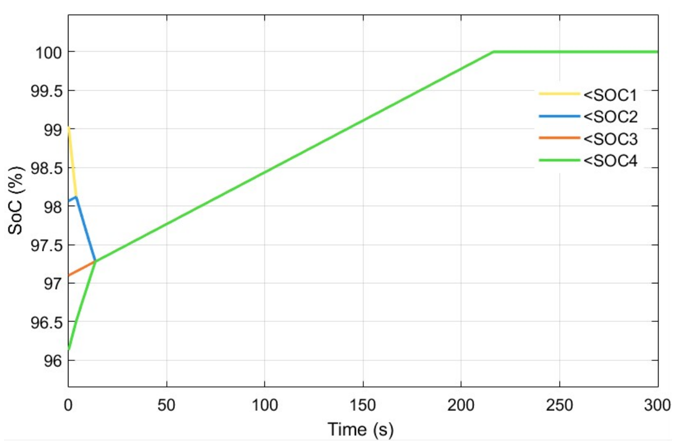

Figure 4. Charging simulation result

Figure 4 illustrates the balancing results during the charging process, where all battery cells are supplied with a fixed current source to achieve full charge. The proposed active balancing mechanism facilitates uniform SoC convergence, optimizing charge distribution and enhancing battery performance. Despite initial SoC

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variations, all cells reach full charge simultaneously, demonstrating the system's effectiveness in energy management. Notably, SoC differences stabilize around 12 seconds, ensuring balanced charging.

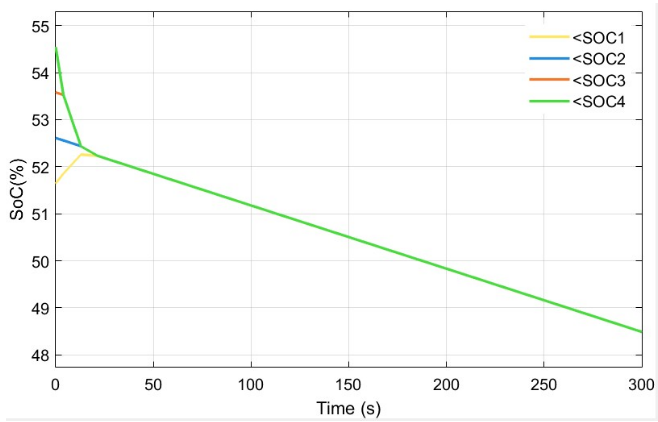

Figure 5. Discharging simulation result

By dynamically redistributing energy, the mechanism mitigates voltage imbalances and enhances safety by preventing excessive charging currents in individual cells. The discharging scenario of the battery pack is analyzed to assess energy distribution effectiveness. Figure 5 shows SoC balancing during the constant current partial discharge cycle. The results reveal that the active balancing system dynamically regulates energy flow, ensuring uniform SoC levels across all cells in approximately 25 seconds. The system compensates for SoC differences by transferring energy to the lowest SoC cell, preventing deep discharge. This approach addresses the common issue of uneven discharging, which can cause premature failure of weaker cells. By redistributing charge continuously, the system enhances battery pack longevity and reliability [25], [26], [27].

By preventing both overcharging and deep discharge, the balancing system significantly enhances battery safety and extends its operational lifespan. Furthermore, it accelerates the process of SoC equalization, rendering it highly suitable for real-world applications. The system ensures stable SoC values throughout both charging and discharging cycles, effectively demonstrating the control strategy's capability to maintain consistent SoC balance and optimize energy transfer between cells.

Conclusions

This study investigates the design and performance of an active cell balancing system for battery management applications, featuring a battery pack with four Li-ion cells (3.7 V, 5.4 Ah). A comparative analysis of active and passive balancing methods, based on existing literature, highlights the inefficiencies of passive balancing, which dissipates excess energy as heat, leading to significant energy losses. In contrast, active balancing optimizes system efficiency by redistributing energy among cells, mitigating SoC imbalances without excessive thermal dissipation.

MATLAB/Simulink simulation results confirm the effectiveness of the proposed active balancing system in

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achieving rapid SoC equalization. The system successfully equalized SoC levels in approximately 160 seconds under steady-state conditions, 25 seconds during discharging, and 10 seconds during charging, demonstrating its efficiency in minimizing initial charge disparities and ensuring uniform energy distribution across the battery pack, thereby extending battery life and improving energy efficiency.

Compared to passive balancing, active balancing provides a more efficient, sustainable solution, particularly in high-power applications where energy efficiency and thermal management are critical. The single-inductor topology employed in this study offers a cost-effective solution, although its performance may be limited when addressing large SoC imbalances. Nevertheless, the results underscore the potential of active balancing to enhance battery performance, operational reliability, and support advancements in energy storage technologies, including electric vehicles.

Future work will explore optimized control strategies, alternative circuit topologies, and the integration of machine learning-based predictive control to improve dynamic response and adaptability under varying load conditions. Further research into multi-inductor or transformer-based balancing circuits could improve SoC equalization efficiency and speed, making the system more suitable for large-scale battery applications.

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