CELL BALANCING OF LITHIUM - ION BATTERIES USED IN ELECTRIC VEHICLES AND MODEL DEVELOPMENT

ABSTRACT

Cell balancing in lithium-ion batteries ensures uniform charging and discharging enhancing efficiency and lifespan. In this work, the active cell balancing and passive cell balancing techniques are optimized by considering voltage, current, temperature and aging factors. This approach aids in designing advanced battery management systems for improved performance and safety. Cell balancing in lithium-ion batteries for electric vehicles faces challenges from capacity variations temperature and aging. Accurate modelling and its simulation in MATLAB/Simulink are complex due to the need for high-fidelity simulations. Furthermore, translating these models into practical solutions for large EV battery packs is also difficult. Thus, the cost-effective implementation remains a key challenge. Cell balancing in lithium-ion batteries ensures uniform charge and discharge rates optimizing performance and battery life. Model development support the design of efficient Battery Management Systems (BMS) to enhance EV performance and safety. For this, the charge conservation method and resistive bleeding techniques are used to balance a battery's charge. Resistors are used in the resistive bleeding technique to release extra energy. These model simulation in application with electric vehicles typically show improvements in voltage uniformity across cells. The findings of this work are improved performance, efficiency and longevity of lithium-ion batteries. Active cell balancing methods are more energy-efficient than passive ones. Overall, the developed model enhances BMS design. It provides valuable insights for future EV battery applications.

Keywords: Active cell balancing, Electric Vehicles, Battery Management System, Charge Conservation, Passive cell balancing, Resistive Bleeding.

INTRODUCTION

Cell balancing in lithium-ion batteries (LIB) ensures uniform charge levels across cells enhancing performance, longevity and safety. Variations in cell characteristics like voltage and capacity can lead to imbalances causing uneven charging or discharging. This can reduce battery life or cause damage including safety risks like thermal runaway. To address these two primary methods are used: passive balancing which dissipates excess energy as heat and active balancing which redistributes charge among cells. Battery Management Systems (BMS) are crucial for monitoring and managing the performance of batteries, ensuring safety, efficiency, and longevity. They track vital parameters like voltage, temperature, and state of charge (SOC) to prevent overcharging, deep discharging, and thermal issues. BMS also helps balance cells within a battery pack, optimizing energy usage. Additionally, they protect against short circuits, overcurrent, and other faults. Overall, BMS enhances battery performance, extends its lifespan, and ensures safe operation in applications like electric vehicles. Hoekstra et al. (2022) have addressed the impact of cell-to-cell imbalance on EV range particularly in aged battery packs and highlights active cell balancing's role in mitigating this issue. A distributed feasibility approach determines optimal balancing currents for maximizing range while a model-predictive controller (MPC) demonstrates a 10% extension in battery End-of-Life (EOL). The proposed MPC outperforms others with efficient balancing at a low C-rate of 1/50C enhancing both range and longevity [1]. Tang et. al. (2021) presents a novel balancing current ratio (BCR) based approach for accurate state-of-health (SOH) estimation in battery packs minimizing reliance on complex cell-level models. By integrating voltage-based active balancing with a weighted fusion strategy the method achieves SOH estimation errors as low as 1.5% significantly outperforming existing algorithms. Hardware-in-the-loop experiments validate its robustness, flexibility and efficiency making it a promising solution for battery health assessment [2]. Paidi et. al. (2022) highlights the critical role of cell balancing in EVs batteries to address SOC imbalances that trigger overcharging or over-discharging protections leading to operational issues. It explores and simulates passive and active cell balancing techniques presenting a hardware prototype for switched shunt resistor-based passive balancing using Arduino IDE (Integrated development environment) and a flyback converter-based active balancing system using MATLAB. The findings demonstrate the effectiveness of these approaches in ensuring battery pack reliability and performance [3]. Nath et. al. (2022) discusses how BMS in EVs use passive and active cell balancing techniques to equalize lithium-ion cells in a battery pack. Passive balancing dissipates excess charge through resistors reducing efficiency while active balancing transfers charge between cells using components like transformers and inductors achieving higher efficiency. Their simulations show the performance of both methods [4]. Einhorn et. al. (2011) describes an active cell balancing method for lithium-ion battery stacks using a flyback DC/DC converter validated through simulations and prototype measurements. Their work demonstrates improved performance by using state of charge and cell capacity as balancing criteria instead of voltage enhancing energy utilization during charging and discharging. A realistic driving cycle comparison highlights the method's efficiency supported by experimental validation [5]. McCurlie et. al. (2016) presents a nondissipative redistributive balancing method for lithium-ion battery (LIB) packs using a fast MPC in continuous time. The MPC optimizes the state of charge (SOC) balance, achieving faster convergence and improved efficiency compared to rule-based algorithms, while also prolonging battery life by reducing unnecessary charge/discharge cycles. Experimental results validate the effectiveness of the MPC coupled with microcontrollers balancing the battery pack in minimal time [6]. Ananda et. al. (2022) describes an improved genetic algorithm-based cell sorting method (GICSA) to optimize LIB performance for spacecraft applications by sorting cells to meet tight constraints. The researcher develops a nonlinear regression model to estimate cell performance in the battery validated with experimental data and showing a root mean square error (RMSE) of 2% for voltage. This approach ensures efficient battery configuration accounting for slight variations in cell behaviour and temperature during operation [7]. Sagar et. al. (2022) addresses the challenges of LIB in EVs and Hybrid Electric Vehicles (HEVs) such as temperature sensitivity and early EOL due to prolonged usage. Their work proposes real-time monitoring for battery reliability and restoration using both a hardware test rig and a MATLAB/Simulink model. It employs Continuous Discharging Test (CDT) and Pulse Discharging Test (PDT) to analyse inconsistencies between the actual and designed battery models [8]. Ekanayake et. al. (2022) introduces a hybrid cell balancing technique combining passive and active methods integrating switched resistor and capacitor balancing to reduce balancing time and power dissipation. The system modelled and simulated in MATLAB/Simulink shows a 30% improvement in balancing time over conventional capacitive balancing techniques. The adaptive control algorithm enhances circuit performance with simple control and hardware [9]. Kumar et al. (2024) presents an analytical performance investigation of a modularized global equalizer system for LIB cell equalization with a mathematical model accounting for energy loss and charging/discharging. Numerical simulations show that the proposed system outperforms others using fewer equalizers and reducing energy loss while maintaining comparable equalization performance [10]. Meti et al. (2021) presents an active cell balancing technique using a Multiwinding and N   Forward Converter (MFC) to enhance the capacity, effectiveness, and lifespan of EV battery packs. The system uses MOSFET switches and a high-frequency transformer with isolated primary and secondary windings to redistribute energy across the cells. The proposed model's cell balancing time is evaluated through simulations in MATLAB Simulink [11]. Babu et al. (2022) compares active and passive cell balancing techniques for LIB emphasizing the importance of a BMS to improve reliability and performance. By modelling a 7.2V, 5.4Ah battery with four cells, the study shows that active cell balancing offers more benefits than passive balancing in terms of battery lifespan. The analysis is conducted through MATLAB/Simulink simulations [12]. Stecca et al. (2022) explores the use of Battery Energy Storage Systems (BESSs) as power redistributors in three-phase grids combining congestion management and energy arbitrage. It examines the impact of low-frequency current harmonics particularly 50- and 100-Hz on the dc-link components including capacitors and battery cells. The study shows that charging with 100 Hz ripple increases degradation by 10%, based on experiments with ICR18650-26F Lithium-ion cells [13]. Jaguemont et al. (2015) presents an electrical and thermal model of a LIB pack for hybrid electric vehicles (HEVs) developed in MATLAB/Simulink to evaluate performance at subzero temperatures. The model incorporates internal resistance effects to predict battery core and crust temperatures and is validated through discharge tests and real working conditions. Simulation results align well with data from an actual HEVs battery pack demonstrating the model's accuracy and effectiveness [14]. Liu et al. (2018) uses advanced battery modelling and multiobjective optimization to derive optimal charging patterns for LIB balancing battery health, charging time and energy efficiency. The optimization is based on a high-fidelity model incorporating electrical, thermal and aging dynamics with constraints on current, voltage, state-of-charge and temperature. The results show that the proposed strategy effectively balances charging speed and efficiency offering health-conscious charging with desirable trade-offs [15]. Samantaray et al. (2022) discusses the use of LIB in electric vehicles (EVs) highlighting their efficiency, lightweight and high-power density. It introduces a battery-powered EV model using an iterative simulation-based method for battery sizing and proposes a simple algorithm for BMS to optimize battery use and protect it from overcharging and over-discharging. The modelling is done using MATLAB/Simulink focusing on key battery parameters like state of charge (SOC), state of health (SOH) and remaining capacity [16]. Arunadevi and Aarthi (2021) presents an automatic cell balancing technique using switched capacitors for multi-cell LIB strings in EV specifically for 16 cells. The proposed method ensures fast balancing speed independent of the number of cells or initial voltage mismatches with a modular architecture for scalability. MATLAB/Simulink models for 4, 8, and 16 cells are developed and simulation results demonstrate the feasibility of the approach [17]. Samanta et al. (2022) introduces a hybrid Fuzzy PID-based control algorithm for nondissipative charge equalization in LIB packs utilizing a supercapacitor and a bidirectional DC-DC converter. The algorithm efficiently balances the cells without requiring precise SOC measurements, reducing computational cost and sensor reliance. Simulation results in MATLAB-Simscape validate the effectiveness and superior performance of the proposed scheme compared to existing methods [18]. Dakshinamoorthy et al. (2023) introduces a hybrid physics-informed neural network (PINN) model for accurately estimating battery temperature in EVs under dynamic driving conditions. The model combines physics-based models with data-driven neural networks, trained on real-world driving simulations achieving higher accuracy and faster computation with less data compared to traditional methods. The proposed approach enhances battery thermal management, improving the reliability and safety of EVs [19]. Hu et al. (2020) presents a novel charging protocol for LIB that optimizes both charging time and capacity fade using a series of constant charging currents. A multiobjective optimization problem is solved through particle swarm optimization (PSO) to determine the best charging current profile. The balanced charging strategy significantly reduces charging time with minimal capacity degradation compared to the standard CC-CV approach [20]. Jeng et al. (2022) investigates the use of autoencoders (AEs) to assess cell inconsistency in a 57-kWh BESS of an electric boat. Four AE models such as fully connected (FC), convolutional neural network (CNN), long short-term memory (LSTM), and CNN-LSTM) were compared with the CNN-LSTM model proving the most effective for complex conditions. The LSTM model excelled in distinguishing normal and abnormal cells, while the FC model performed best under abnormal battery conditions [21]. Soni et al. (2021b) uses genetic algorithms to estimate energy balance and battery performance in spacecraft, incorporating open-circuit voltage, internal resistance, and coulomb counting. It accurately matches terminal voltage and estimates deliverable capacity for various battery configurations. Validated against experimental data, the model achieves 1% accuracy for voltage and 2% for capacity estimation [22]. Busquets-Monge et al. (2019) presents a multilevel multiphase Direct Current-Alternate current (DC-AC) conversion system using a neutral-point-clamped converter with multiple battery packs balancing their SOC efficiently. The system ensures optimal battery capacity usage even with varying SOC or capacities through lossless power distribution. Verified by simulations and experiments, this approach offers a scalable and efficient solution for power conversion across various battery configurations [23]. Prajwowski et al. (2020) explores the energy recovery potential in hybrid electric vehicles using nickel-metal hydride (NiMH) batteries, focusing on key parameters like voltage, current, and state of charge. Tests on a Toyota Prius revealed variations in voltage and discharge/charge currents influenced by road conditions and electric machine torque balance. The study uses a Three RC Network Model to accurately estimate the NiMH battery's performance achieving up to 2.93% accuracy in real-world conditions [24]. Yang et al. (2023) describes a deep reinforcement learning-based fast-charging control framework for electric vehicle batteries aiming to minimize charging time while preventing damage. The approach uses a cell-to-pack equalization topology and formulates the problem as a multiobjective optimization, considering charging time, consistency and safety. Simulations and experiments demonstrate the framework's effectiveness in achieving faster charging and improved balancing, with real-time applicability [25]. Samanta et al. (2022) describes an active charge balancing scheme using a supercapacitor and bidirectional DC-DC converter for efficient cell-to-pack-to-cell (C2P2C) balancing in LIB packs. The system ensures optimal capacity utilization, safety and longevity by balancing cells during charging and discharging. Simulations in MATLAB-Simscape show that the scheme offers high balancing speed reduced component needs and robustness outperforming similar topologies [26]. Ahmad et al. (2023) focuses on improving cell balancing in LIB using combined phase-shifted and boost DC converters for parallel charge balancing. The proposed method enhances the overall efficiency of the BMS by balancing both same-string and parallel strings of cells. MATLAB/Simulink simulations using a Li-ion NMC (Nickel Manganese Cobalt) cell model demonstrate the effectiveness of this approach [27]. Vishnu et al. (2021) describes smart dynamic cell equalizer using a forward converter to address variations in internal resistance, capacity and self-discharge rate among Li-ion cells in a battery pack. The equalizer ensures near-equal SOC levels across all cells, improving performance and reducing battery aging. MATLAB/Simulink simulations validate the method demonstrating effective SOC balancing in dynamic conditions without additional circuits [28]. Soni et al. (2023) focuses on the performance analysis and validation of a 48V LIB pack for electric vehicles, emphasizing charging, discharging, and cell balancing techniques. A BMS is designed to enhance battery life, drive performance, power management, and safety. MATLAB/Simulink simulations demonstrate the effectiveness of the proposed system in improving battery performance and security [29]. Gupta et al. (2022) discusses passive cell balancing for LIB, addressing unbalanced cell voltages due to variations in parameters like SOC, impedance and temperature. The study includes an online passive balancing experiment and a Constant Current/Constant Voltage (CCCV) charging topology to prevent overcharging. MATLAB/Simulink simulations validate the proposed system's effectiveness in maintaining balance and ensuring safe charging [30]. Research gaps are LIB degrade over time due to factors like capacity fade and internal resistance increases, which can lead to imbalanced cells that affect overall battery performance and safety. Active balancing systems, which redistribute charge between cells tend to be more complex and costly due to the need for specialized circuitry and control systems. Many current cell balancing techniques work well for smaller battery packs but face challenges when scaling up to the large battery packs used in EVs, which may contain hundreds of cells. Existing cell balancing models and its simulation in MATLAB often focus on specific aspects such as voltage or temperature without comprehensive cross-platform simulations that integrate the entire battery system including the charger, inverter and vehicle dynamics. Our objectives are to Develop a Simulink model of a battery pack in

MATLAB by using charge conservation method for active cell balancing and by using Resistive Bleeding method for passive cell balancing in such a way that its efficiency becomes maximum at low operational cost, without affecting environment as well.

ACTIVE CELL BALANCING

In active cell balancing, inductors play a key role in efficiently managing and redistributing energy between the cells of a battery pack. The primary function of an inductor in this process is to store and release energy in the form of a magnetic field, which helps balance the voltage levels across cells without wasting energy. When one cell is overcharged (its voltage exceeds the desired level), the inductor is used to transfer excess energy from that cell to a lower-voltage cell or a storage capacitor. The process works by using a power converter circuit, which often includes an inductor in the energy transfer loop. When the balancing circuit detects an imbalance in the voltage of cells, the excess energy from the higher-voltage cell is directed through the inductor. The inductor momentarily stores this energy as a magnetic field, and then releases it to a lower-voltage cell or capacitor. It helps to prevent overheating and energy loss that occurs in passive balancing, where excess energy is dissipated as heat. Inductors are especially effective in this role because of their ability to regulate the current flow, ensuring that energy is transferred smoothly without sharp voltage spikes or losses. This process continues until all cells in the battery pack are balanced, meaning they each have similar voltage levels. The use of inductors in active balancing is far more efficient than passive balancing methods. Active balancing preserves the battery's total energy by redistributing it rather than discarding it as heat.

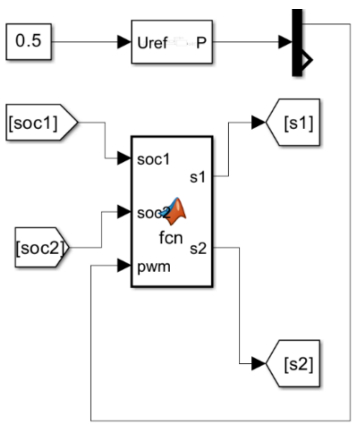

Figure 1: Control loop diagram in MATLAB

Figure 1 shows the states of charge of batteries are controlled by using MATLAB program where we use PWM Signal, to operate A PWM (Pulse Width Modulation) signal can be generated using 4 lines for different purposes, typically in a scenario where multiple PWM signals are needed for controlling different devices like motors, LEDs, or other actuators. Each of these lines would carry a PWM signal that could control a separate device. Each line has a square wave signal where the on-time (high) and off-time (low) define the duty cycle.

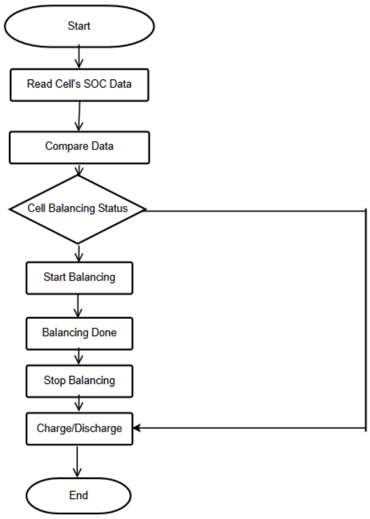

Figure 2: Flow chart

The flow chart as shown in Figure 2 represents how the state of charge of batteries will goes on in Active Cell Balancing Method. Figure 3 shows the control circuit used for the ACB method.

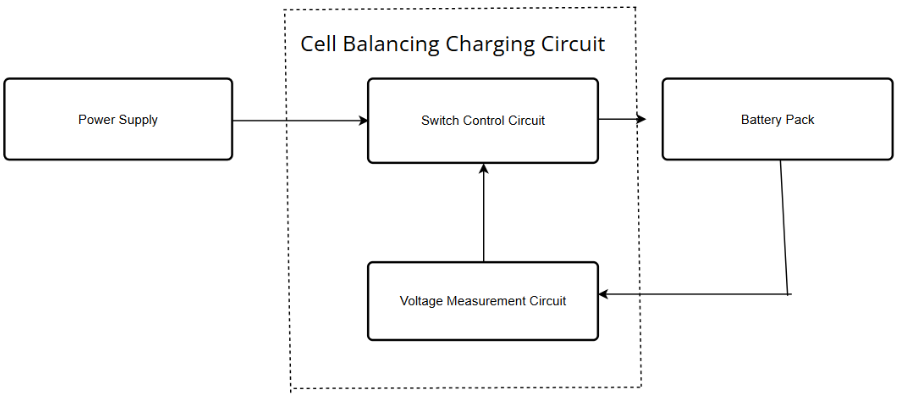

Figure 3: Control Circuit for Active Cell Balancing Method.

PASSIVE CELL BALANCING

In passive cell balancing, the resistive bleeding method works by dissipating excess energy from overcharged cells as heat, thereby reducing the voltage of those cells to match the others in the battery pack. When a cell's voltage exceeds a set threshold, a resistor is activated across the cell to "bleed off" the surplus energy. This resistor allows current to flow through it, converting the excess energy into heat. The process is controlled by a balancing circuit that continuously monitors the voltage of each cell. The resistive bleeding method is simple and cost-effective but comes with inefficiencies. Energy is lost as heat, which not only reduces overall efficiency but also can increase thermal stress on the cells. This method does not redistribute the energy to undercharged cells, meaning the excess energy is simply wasted. It is commonly used in situations where cost is more important than maximizing efficiency, as it requires fewer components compared to active balancing methods. While it helps maintain balanced cell voltages, the resistive bleeding method is less energy-efficient.

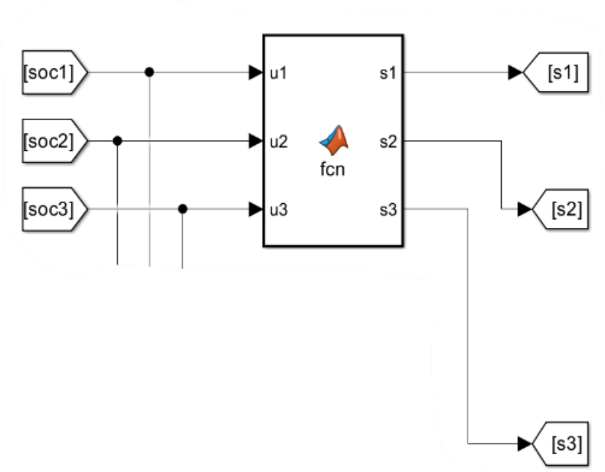

Figure 4: Control loop diagram in MATLAB

Figure 4 shows the state of charge of batteries is controlled by using MATLAB program in Passive Cell Balancing Method. Figure 5 schematically represent the control circuit used for PCB method.

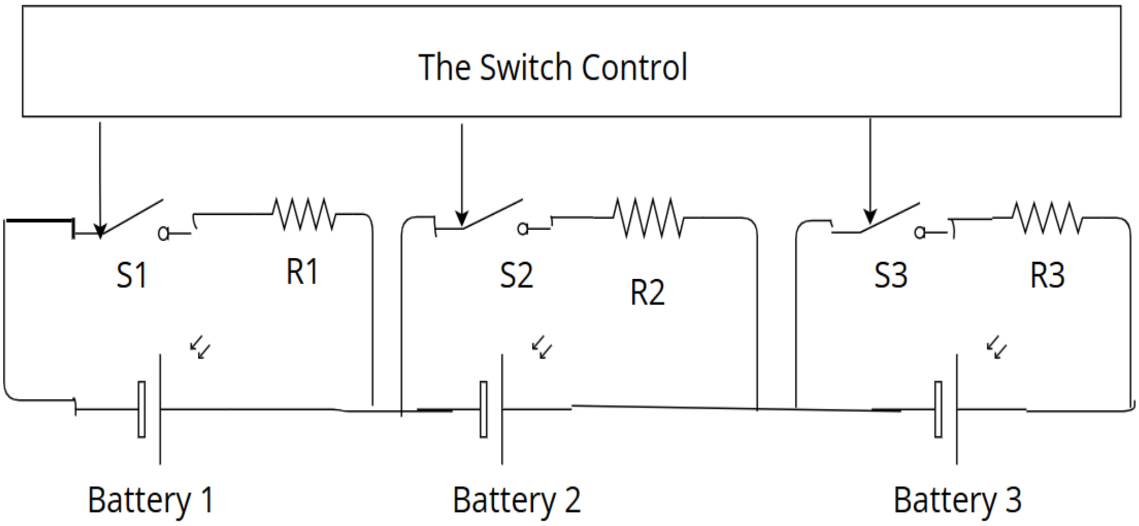

Figure 5: Control circuit for Passive Cell Balancing Method.

SIMULATION RESULTS AND DISCUSSION

The designed SOC method is simulated in MATLAB/Simulink environment. As shown in Table 1, the time interval 0 sec to 10 sec represents 'fast charging zone', time interval 10 sec to 150 sec indicates 'normal charging zone' and time elapsed after 150 sec represents 'long time charging zone'.

TABLE 1: Active Cell Balancing

Battery	(%) State of Charge of Battery at different time (sec).					
	T=0	T=10	T=30	T=80	T=150	T=200
Battery 1	23	42.82	56.74	82.06	100	100
Battery 2	41	42.82	56.74	82.06	100	100

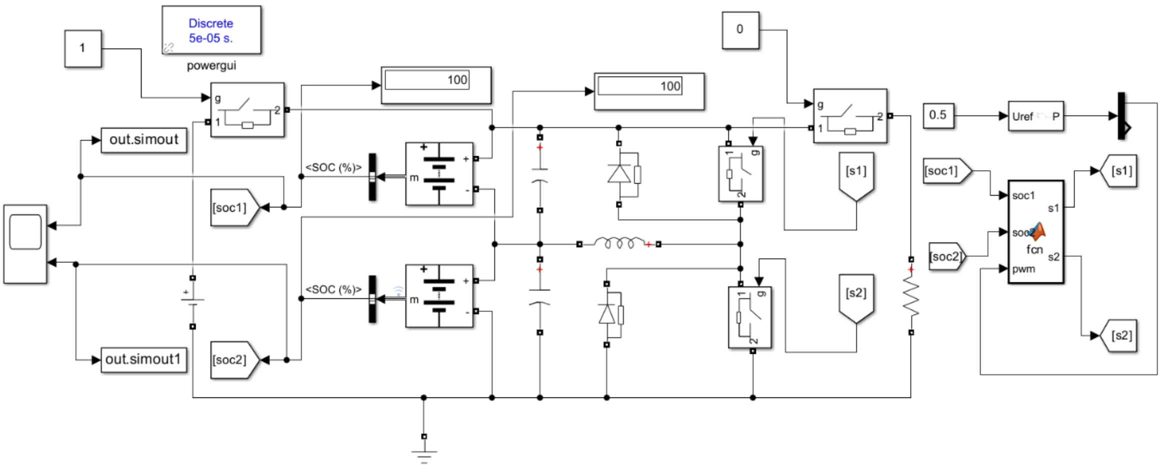

Figure 6: Simulink Model of a battery at 200 sec in Active Cell Balancing.

In Figure 6 basically shows that Simulink model of a battery at 200 sec in active cell balancing, in which two batteries gets 100% state of charge (SOC) at 200 seconds.

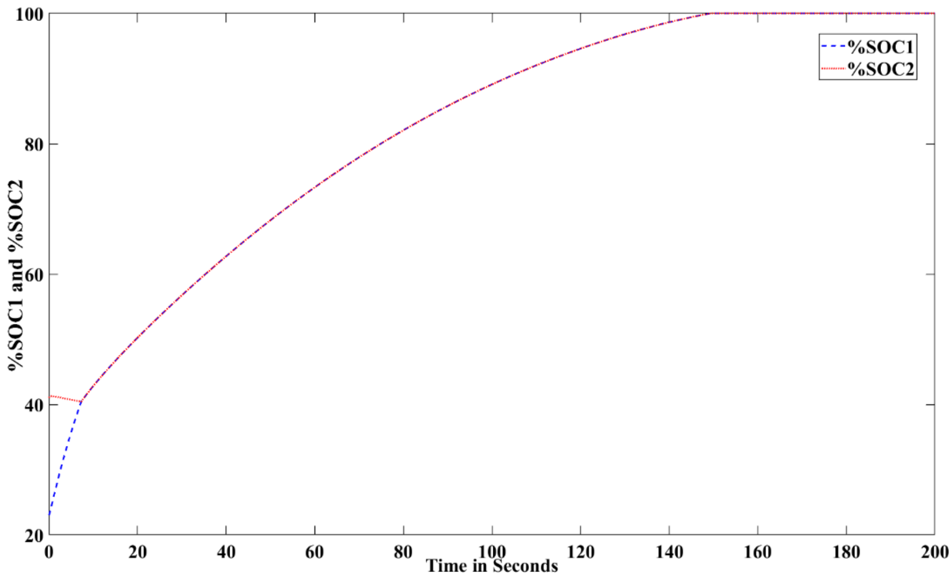

Figure 7: Cell balancing of Two Batteries at 200 sec.

Figure 7, it is clearly shows that the active cell balancing of two batteries having different initial state of charge, by redistribution of charge method these two batteries get balanced. As table and figure shows that equal state of charge achieved at different time (seconds) irrespective of their initial state of charge.

TABLE 2: Passive Cell Balancing

Battery	(%) State of Charge of Battery at different time (sec).	
	T=0	T=3000
Battery 1	40	26.5
Battery 2	50	26.5
Battery 3	30	26.5

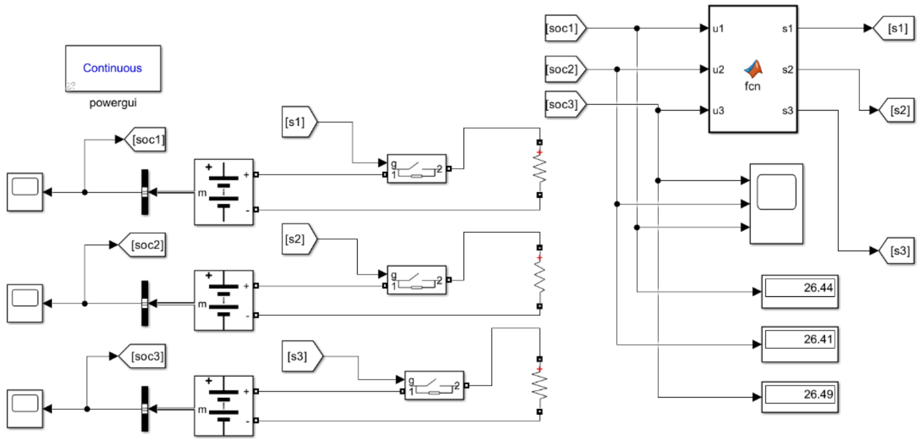

Figure 8: Simulink Model of a battery at 3000 sec in Passive cell Balancing.

In Figure 8 it basically shows that Simulink model of a battery at 3000 sec in passive cell balancing, in which three batteries gets equal state of charge (SOC) at 3000 seconds.

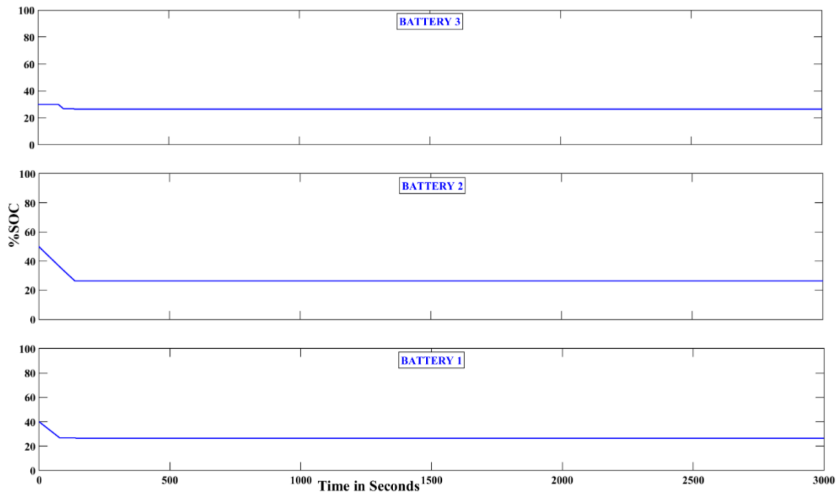

Figure 9: Cell balancing of three Batteries at 3000 sec.

Figure 9 shows that the passive cell balancing of three batteries having different initial state of charge, by using resistive bleeding method these three batteries get balanced at t=3000 seconds. Resistive bleeding is a passive cell balancing method used in battery management systems to equalize the charge across individual cells. It works by dissipating excess energy from higher-charged cells as heat through resistors. This prevents overcharging and ensures all cells maintain a balanced state of charge. From Table 2 we observed that the three batteries get equal state of charge (SOC).

CONCLUSION

This paper explores and simulates various cell balancing techniques using MATLAB highlighting their advantages and limitations. PCB stands out for its simplicity and ease of implementation. It uses a resistor-bleeding method to dissipate excess charge in the form of heat. However, this leads to significant energy loss in the form of I^2R losses which can adversely impact the circuit thermally. To address these issues, ACB methods are employed to reduce charge loss during the equalization process. Among these, the inductor-based model is a popular approach. Despite its advantages, the conventional inductor-based method suffers from long equalization times, making it less efficient for certain applications. To overcome this limitation a novel inductor-based balancing method is proposed, which organizes cells into groups and balances them group by group. This approach significantly reduces equalization time while maintaining efficiency. Although passive balancing is straightforward, it is less suitable for applications requiring energy efficiency and thermal management. Active techniques particularly the improved inductor-based method provide a more effective solution for managing charge discrepancies in battery cells. These findings underscore the importance of optimizing cell balancing techniques for practical energy storage systems ensuring efficient performance and reliability.

SCOPE FOR FUTURE

The future scope of cell balancing in lithium-ion batteries is crucial for optimizing battery performance, lifespan, and safety in a variety of applications, including electric vehicles (EVs), renewable energy storage, and portable electronics. Cell balancing ensures that each cell in the battery pack maintains a similar voltage level, preventing certain cells from being overcharged or undercharged, which could lead to reduced performance or potential failure. Effective cell balancing can help maximize the overall capacity and efficiency of the battery, allowing for more energy to be stored and delivered. By maintaining uniform charge levels across cells, it reduces the risks of overcharging and thermal runaway, ensuring safer battery operation. In the future, advanced cell balancing techniques, especially active cell balancing**,** are expected to play a significant role in extending battery life and improving energy efficiency. Active balancing redistributes energy between cells, minimizing waste and enhancing the overall performance of the battery. As demand for high-energy-density batteries grows in industries like EVs and grid storage, cell balancing will be key to reducing operating costs, enhancing battery lifespan, and improving sustainability. Moreover, with the integration of smart Battery Management Systems (BMS), real-time monitoring and dynamic adjustment of cell voltages will become more precise, further enhancing the longevity and safety of lithium-ion batteries.

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