Analysis of Cell Balancing Algorithms in Battery Management System

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Abstract: Environmental support for eco-friendly transportation systems have positioned electrical vehicles (EVs) as vital tools in the fight against global warming and as effective means to reduce reliance on fossil fuels. To achieve this, EVs depend on long life batteries supported by an advanced battery management system (BMS). A primary task of the BMS is cell balancing, which regulates both the state of charge (SoC) and voltage of each cell to improve the system's efficiency, durability, safety, and lifespan. Imbalances among cells in a battery pack often due to random connections or usage variations can lead to issues such as overcharging, undercharging, accelerated degradation, or even pack failure. This paper explores advanced cell balancing algorithms, focusing on SoC and voltage control methods, and smart BMS control strategies to enhance cell balancing efficiency, contributing to the development of longer lasting EV technology.

1 INTRODUCTION

A robust BMS is crucial for the efficient operation of electric vehicles, emphasizing monitoring, reliability and continuous advancements to address current challenges (Prakasha et al., 2022). In Electrical vehicles maintaining cell balance is vital for maximizing usable capacity, efficiency, and battery lifespan. Typical methods include voltage and SoC balancing, with innovations targeting imbalances in individual cells. These advancements refine real time detection of unbalanced cells, improving the safety, lifespan, and overall efficiency of battery systems (Piao et al., 2015). Cell balancing methods are crucial for managing battery packs with multiple series cells, especially in EVs. These techniques focus on aligning the SoC across cells to maximize overall functionality, enhance safety, and prolong battery life. Various algorithms address voltage mismatches that stem from production differences, temperature shifts, and discharge profiles. Yet, many traditional approaches emphasize voltage balancing without accounting for deeper causes of imbalance, which can reduce balancing effectiveness. A comprehensive understanding of these algorithms is key to boosting battery systems reliability and efficiency, aiding in the broader adoption of EVs and advanced battery technologies (Barsukov et al., 2009). lithium ion batteries, favored for their substantial energy density, are commonly used in EVs. Ensuring safe operating conditions is critical, as exceeding these limits may reduce lifespan or lead to risks like thermal runaway (Pro¨ bstl et al., 2018).Various DC DC converter topologies, like bidirectional Cuk and flyback converters are essential in active cell equalization, often achieving over high efficiency. The selection depends on the specific design needs, with ongoing research aimed at improving energy efficiency and performance for reliable electric vehicle battery packs (Miranda et al., 2023). Analyzing the algorithms employed in DC-DC converters is essential for enhancing efficiency, performance, and stability in a wide range of applications. These algorithms are generally divided into two main categories: conventional methods and artificial intelligence-based methods. Recent advancements have enabled the integration of enhanced techniques that significantly improve the performance of DC-DC converters,

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especially in conductance modes and microgrid systems (Li et al., 2017).

2 LITERATURE SURVEY

Balancing of cells is critical in BMS to preserve SoC and voltage of the battery cells. Vibrations and other deviations during manufacturing together with chemical degradations can lead to cell overcharge or deep discharges hence compromising on its performance and its life expectancy. Depending on its nature, balancing methods are passive or active. Active balancing techniques like switched capacitor and DC-DC converters (Lee et al., 2016) try to redistribute charge for balance. On the other hand, passive balancing techniques ensures that overcharged cells expel energy through fixed or switchable shunt resistors. It seeks to clearly elucidate the various differences between active and passive strategies (Babu and Ilango, 2022). While passive battery balancing has its key advantages, it can be seen disadvantageous because efficiency drops with the surplus energy that is converted to heat in resistors. In other words, depending on the charge level of the cell with the lowest capacity, the capacity of the whole system of batteries also changes and some adaptations must be made accordingly (Deja, 2019).

Shunting resistor techniques(Daowd et al., 2011) in passive balancing release excess energy as heat, making them inefficient for low-power systems. Fixed shunt resistors continuously divert current, while switched shunt resistors enable controlled discharge, both causing energy loss. Active balancing (Rovianto et al., 2024) ensures equalized currents and voltages, enhancing energy density, reducing thermal stress, and increasing battery life. Methods like capacitor, inductor, and transformer based balancing (Khoshkbar-Sadigh et al., 2021) redistribute energy using DC-DC converters improving performance. Equalization structures (Marcin et al., 2023)include cell-to-cell, cell-to-battery, battery-to-cell, and bidirectional setups, optimizing energy transfer. DC-DC converters (Verma et al., 2013)in BMS manage voltage and current effectively, employing advanced control techniques to enhance reliability and system efficiency.

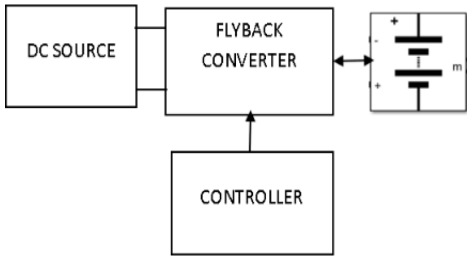

Figure 1: Flyback Converter

Figure 1 shows a flyback Converter with a DC source and controller. The converter regulates power to the load using a transformer for isolation and voltage control. It has low conduction loss and is cost-effective, making it an efficient solution for energy transfer (Selvaraj and Vairavasundaram, 2023). The control algorithm operates in conjunction with bidirectional flyback DC-DC converter (Simcak and Danko, 2021) to achieve efficient energy transfer and the SoC balance among various battery cells. The algorithm initially establishes the SoC of the battery cells and uses the forgetting factor recursive least square–extended Kalman filter (FFRLS-EKF) algorithm to monitor and to estimate these SoC levels continuously. First it determines what is the lowest and highest SoC batteries to build an equalization group for energy transfer. If the cell with the highest SoC discharges directly into the cell with the lowest SoC, the SoC of the weaker cell will increase in the first mode of operation. To enable more efficient energy sharing, subsequent equalization modes employ multiple higher SoC cells discharging their energy to lower SoC cells in order. The converter operates according to the algorithm's control and constantly adjusts the energy transfer value according to the SoC states of the cells in real time. The equalization process is continuous, guaranteed to continue until the SoC values are balanced within the specified range, through continuous monitoring and dynamic adjustment. In this work, the integration of both the Active Cell Equalization Algorithm and bidirectional flyback converter improves overall efficiency and performance, while also addressing the issue of SoC inconsistencies across the battery cells(Qin et al., 2022).

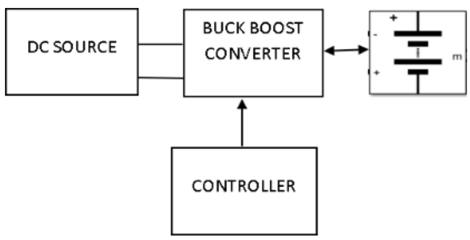

Figure 2: Buck Boost Converter.

Figure 2 shows a buck-boost converter with a DC source and controller that adjusts voltage based on load requirements. These converters are compact, efficient and ideal for applications with fluctuating input voltages, like battery management and energy storage (Yi and Wang, 2023). The cell balancing algorithm uses buck-boost converters to balance the SoC of series connected lithium ion battery cells. Through closed loop control with PI controllers (Yeoh et al., 2022), the algorithm switches between Buck and Boost modes to optimize energy transfer. PWM signals regulate switches for efficient energy transfer, ensuring equal SoC and improving battery cycle life and power delivery (González-Castaño et al., 2021). A reconfigurable converter, operating as a boost converter, is utilized in the balancing system to manage a battery voltages. Controlled by PI controllers (Wan et al., 2023), the boost converter facilitates voltage synchronization across the battery cells. In no load conditions, small signal modeling is used to derive the control equations. Under load conditions, a dual loop control strategy is employed, consisting of a high bandwidth inner current loop and a slower outer voltage loop. This strategy efficiently balances the SoC across the cells, as demonstrated in simulations with lithium ion batteries.

The algorithm explains the use of modified bidirectional Cuk converters in DICM for battery cell balancing in lithium ion battery packs. A serially connected battery pack model with equalizers is designed and an optimal control method based on the conjugate gradient method (Ouyang et al., 2016) is implemented to minimize energy loss and rapidly reduce the differences in SoC. The algorithm controls currents by modifying the PWM duty cycles of the MOSFETs, ensuring optimal safety and performance. Simulations highlight the effectiveness of this method in achieving the quick SoC convergence with minimal effort.

A SoC based centralized control approach for an active balancing algorithm using a centralized DC-DC converter system, which is a non isolated power converter, is employed in Constant Current (CC). Since it monitors the SoC of every battery cell continuously in a battery pack to balance its SoC levels, hence battery job performance and life is improved. Our algorithm keeps the current constant during the balancing process using SoC data, so that energy can be redistributed efficiently among the cells. For uniform charge distribution, cells with higher SoC transfer excess energy to cells with lesser SoC. A SoC based centralized control facilitates achieving maximum energy transfer rates and minimizing energy losses as well as protecting against over charging or over discharging. CC mode integration provides stable current flow, which makes the balancing process robust, at the cost of sophisticated control strategies and accurate SoC estimation to execute properly(ELVIRA et al., 2019).

The proposed voltage balancing scheme combines zero sequence signal injection (ZSI) and Redundant Level Modulation (RLM) for a four-level Neutral Point Clamped (NPC) converter(Wang et al., 2020). The reference voltages of all phases are first subjected to ZSI, then the duty ratios of the top and bottom capacitors are adjusted based on neutral point currents to minimize voltage deviation. RLM is used next to control the middle capacitor voltage by adjusting the duty cycle of the dominant phase. This dual mechanism results in the cancellation of capacitor voltages and reduces switching transitions, enhancing converter efficiency and performance.

The algorithm used here is the Amortized Q-learning (AQL) algorithm (Karnehm et al., 2024), an enhancement of the traditional Q-learning model, specifically designed to balance the SoC in reconfigurable batteries. Unlike traditional Q-learning, which faced memory limitations when controlling more than seven modules, AQL addresses this issue, enabling control of up to 12 modules. The approach combines machine learning with algorithmic control, allowing it to manage complex scenarios such as idle cells or safety concerns like thermal runaway. Experimental results, tested on both a hybrid cascaded multilevel converter and BM3 converter simulation, validate the algorithm's effectiveness, though it is 20.3% slower in balancing compared to previous methods. Despite its higher computational complexity, the AQL algorithm offers advantages, such as reduced switching times, making it suitable for reconfigurable battery applications in DC sources.

The battery pack utilizes a half-bridge configuration with two complementary switches for each cell (Sorouri et al., 2024), enabling selective bypassing to balance the SoC and prevent rapid discharge of low SoC cells. The architecture integrates an Artificial Neural Network (ANN) that actively manages the SoC by generating PWM signals. These signals are based on the variance of each cell's SoC in relation to the average SoC, allowing for efficient balancing of the battery cells. This system models each cell as a circuit with resistor capacitor pairs, and the ANN processes input data, adjusting the duty cycle signals for precise control of half-bridge switches. The objective is to minimize SoC variations while maintaining cells within a safe operating range, thus improving overall battery performance and longevity.

The cell balancing system uses modular low voltage bypass DC-DC converters connected in a series input, parallel output configuration to equalize the SoC of battery cells and supply an auxiliary low voltage load (Rehman et al., 2015). Each bypass converter operates autonomously, using a PI controller to regulate the low voltage bus voltage and droop control to balance the SoC of the cells. The droop control ensures stable load current sharing without a communication links by introducing a virtual droop resistance, which damps oscillations and maintains system stability. The results confirm effective SoC balancing and stable operation for a three cell lithium ion Nickel Manganese Cobalt Oxide battery pack.

An Adaptive Model Predictive Control balancing algorithm (Salamati et al., 2017) is proposed to balance cell voltages across a series connected lithium ion battery stack and uses a multi winding flyback converter to achieve voltage balance efficiently. First, the voltages of each cell are measured by the central controller, sorted from highest to lowest and the future voltage behavior of each cell is predicted with Recursive Least Squares identification. If the cell voltage difference between two terminals exceeds some defined threshold then the balancing process is initiated. Then the controller strategically discharges the cell with the highest voltage by turning on its corresponding switch and calculates when the current would reach a predefine peak. The controller divides this discharge process into two equal stages, selecting optimal combinations of switches for the second and third highest voltage cells to minimize voltage standard deviation within the stack. The method uses the predictive models to adjust the switch states to balance current flow and uniform SoC distribution which results in reducing voltage differences as well as increasing the battery performance.

This decentralized structure enables the hybrid droop control algorithm to be effectively used in BMS (Chowdhury and Sozer, 2020), where each battery cell is paired with its own DC-DC converter, enhancing reliability by removing communication links. The algorithm employs dual droop control, where virtual resistance is used to regulate voltage and virtual admittance is applied to control current, allowing for the adjustment of reference values. It ensures SoC based power sharing, dynamically regulates direct current bus voltage and corrects voltage errors through closed loop control. A controller processes current discrepancies to generate the MOSFET gate signals, demonstrating effective SoC equalization and suitability for distributed energy storage systems.

The balancing algorithm works by checking the SoC of each cell in the battery pack(Zhou et al., 2023). A two layer controlling strategy is implemented, whereby the first layer selects the balancing action based on the current SoC values, and the second layer fine tunes the control signals with fuzzy logic to achieve the optimum path of energy transfer between cells. The algorithm activates corresponding switches in the converter circuits to allow energy flow from higher SoC cells to lower SoC ones, to maintain uniform voltage levels over all cells. Dynamic resizing enhances battery health and efficiency.

Table 1: Acronyms.

Acronym	Description
EVs	Electric Vehicles
BMS	Battery Management System
SoC	State of Charge
DC	Direct Current
PI	Proportional-Integral
PWM	Pulse Width Modulation
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
FFRLS-EKF	Forgetting Factor Recursive Least Squares–Extended Kalman Filter
ZSI	Zero-Sequence Signal Injection
AQL	Amortized Q-learning
CC	Constant Current
RLM	Redundant Level Modulation
BM3	Battery Modular Multilevel Management
ANN	Artificial Neural Network
AMPC	Adaptive Model Predictive Control
RLS	Recursive Least Squares

Table 1 provides a summary of key acronyms used in the research. Table 2 provides an analysis of various balancing topologies and algorithms used in BMS, focusing on both voltage and SoC balancing. The table outlines the equalization structure, converter types (isolated and non-isolated), algorithms and the merits and demerits of each topology. It highlights key factors such as efficiency, energy utilization and control complexity. This analysis offers a comprehensive comparison that helps in understanding the relative strengths and weaknesses of different methods in practical applications. By presenting this information in a well structured manner, it provides valuable guidance on selecting the most appropriate technique based on factors such as cost, scalability and compatibility with existing systems. This overview proves to be indispensable for researchers and engineers, aiding in the development of optimized and robust BMS for various applications.

Table 2: Analysis of Different Balancing Structures and Algorithms in Battery Systems Based on Converters.

Balancing Topology	Equalization Structure	Converter Type	Algorithm	Merits	Demerits	Voltage	SoC	References
Flyback Converter	Cell to Cell	Isolated	FFRLS method for model parameter identification EKF method for SOC estimation	Efficient energy utilization Advanced SOC estimation	Algorithm complexity Dependence on accuracy		✓	(Qin et al., 2022)
Buck-Boost Converter	Cell to Cell	Non-Isolated	PI Controllers PWM Control	Efficient energy transfer Quick balancing	Complex design High cost		✓	(Yeoh et al., 2022)
Boost Converter	Cell to Cell	Non-Isolated	PI Control	Stable operation Flexible operation	Energy losses in converter Controller dependency		✓	(Wan et al., 2023)
Cuk Converter	Cell to Cell	Non-Isolated	Optimal Control using Conjugate Gradient Method	Adaptive duty cycle control Optimal control	Energy loss during mode transitions PWM frequency limitations	✓	✓	(Ouyang et al., 2016)
Power Converter	Cell to Cell	Non-Isolated	Constant Current (CC) Mode SOC-Based Centralized Control	High speed Efficient transfer	Control complexity Requires precise SOC estimation		✓	(ELVIRA et al., 2019)
Four-Level NPC Converter	Cell to Cell	Non-Isolated	Closed-loop balancing with RLM Level-shifted carrier PWM	Wide modulation range Simple implementation	Increased switching losses More transitions	✓		(Wang et al., 2020)
Half-Bridge and BM3	Cell to Cell	Non-Isolated	Amortized Q-learning for SOC balancing	Combines control with ML Balances SOC	Slower than conventional Memory limitations		✓	(Karnehm et al., 2024)
Half-Bridge Converters	Cell to Cell	Non-Isolated	Artificial Neural Network (ANN)	ANN for SOC balancing Optimal bypassing	Computational overhead Reliability issues		✓	(Sorouri et al., 2024)
Bypass Converter (Dual Active Bridge)	Cell to Cell	Isolated	Combined droop control PI controller	Efficient autonomous balancing Improved stability	Prolonged balancing Unidirectional limit		✓	(Rehman et al., 2015)
Flyback Converter	Cell to Cell	Isolated	AMPC for cell equalization RLS for voltage prediction	Efficient prediction Improved performance	Computational complexity Prediction reliance		✓	(Salamati et al., 2017)
DC/DC Converter	Cell to Cell	Isolated Non-Isolated	Hybrid Droop	Increased reliability Effective SOC equalization	Complex design Parameter sensitivity	✓		(Chowdhury and Sozer, 2020)
Inductor Converter	Cell to Cell	Non-Isolated	Fuzzy Logic	Improved efficiency Extends lifespan	Complex strategy Higher costs		✓	(Zhou et al., 2023)

3 CONCLUSIONS

This paper evaluates the algorithms used in balancing methods for BMS in electric vehicles . These algorithms are designed to improve the energy and optimize the dynamics of energy transfer within battery cells. As a result, battery packs become more reliable, durable and capable of performing efficiently in high energy demand applications. Balancing is enhanced through the use of advanced DC-DC converters that regulate voltage and energy requirements assisted by the various algorithms to ensure efficient regulation. Choosing the right control algorithm remains a complex task, factoring in computational load, real time adaptability, power consumption and application relevance. The future advancement of battery management systems will depend on a deeper understanding of these algorithmic solutions, which must be further refined to achieve optimal performance and prolong battery life.

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