A Hybrid Active and Passive Cell Balancing Approach for Battery Management Systems in Electric Vehicles

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***Abstract*—Battery's safety management system can be abbreviated as BMS. An electronic battery management system which charges the battery rechargeable. It keeps track of the battery to make sure it is safe to use. The main purpose of it to keep a tab on the battery. The status of battery monitors the voltage temperature current etc. The battery may comprise a single cell or a module. There are a few cells in this module. The battery pack contains many modules. The calculation of secondary data is performed by BMS. Secondary data includes SOC, SOH (state of health gas), and others. A battery management system protects the battery from operating outside its safe requirement. An emission test checks the exhaust system of an automobile. It is a verification of whether the automobile vehicle meets the pollution standards set by law. All vehicles require a particular emission standard for their vehicles. The testing of a gas analyzer instrument is according to the ISO 17025 emission standard. The specialized gas analyser checks the toxic or noxious emissions released by a vehicle. The noxious gases they test include CO, CO2, NO and HC. Once the law prescribes the emission standard of the vehicle, it seeks certification and the corresponding documentation of the emission model.**

***Index Terms*—Battery Management System, Cell Balancing, Electric Vehicles, Passive Balancing, Active Balancing, MATLAB Simulink, State-of-Charge (SoC), State-of-health (SoH).**

I. INTRODUCTION

The lithium-ion battery has become a favorite energy storage source for use in electric cars and power grids among others, thanks to its high energy density, efficiency, and lifespan. As these applications demand higher power and capacity, battery packs are typically formed by connecting multiple cells in series and parallel configurations. However, such arrangements inherently introduce challenges related to cell imbalance, which can have a significant impact on the performance and safety of the overall system.

Cell imbalance primarily arises due to variations in manufacturing processes, differences in internal resistance, unequal thermal conditions, and non-uniform aging characteristics. These aspects cause variations in the voltage level and state-of-charge among the individual cells when charging and discharging is going on. Therefore, in the case of a series connection of the cells, the capacity of the entire pack depends on the weak cell within the series. In severe cases, imbalance can also lead to overvoltage or undervoltage conditions, causing serious safety concerns.

In order to counterbalance these problems, a cell balancing process is introduced in the battery management system (BMS). Conventional methods of passive cell balancing de- pend on energy dissipation from high voltage batteries by utilizing resistors [2], [3]. While such methods are simple and cost-effective, they suffer from energy loss in the form of heat, making them less suitable for high-energy applications. In contrast, active balancing techniques enable energy transfer between cells using capacitive or inductive elements, thereby improving energy utilization and reducing thermal stress [5], [6]. Despite these advantages, active methods involve in- creased circuit complexity and control requirements.

Modern developments in Electric vehicles EVs in the design of BMS with respect to the aspect of cell balancing have concentrated on hybrid balancing techniques that utilize ad- vantages offered by both the types of cells balancing methods which are passive and active methods [1]. This approach allows the system to choose according to cell status and efficient transfer of energy in case of high imbalance in state of charge or voltage levels, and dissipative actions in case of low imbalance. Thus, it not only speeds up balancing but also increases efficiency of the whole battery pack.

By doing analysis and validation of various balancing methods using simulation environments like MATLAB reveal very important information regarding their concept behind the idea, working and effectiveness or how it effects of these balancing techniques namely passive and active balancing. Many factors can be used to measure the system performance among them parameters like the duration or speed at which the voltage balance among the cells, energy losses and the thermal effect, like how much heat is being bled from the cells. In this paper an intelligent control approach is used where based on parameters like voltage and SOC differences is used to improve the efficiency of balancing systems in different operating conditions. Cell balancing techniques continue and will definitely play an important role in battery reliability, efficiency, and safety thus keeping the system and ev safe.

II. BATTERY MANAGEMENT SYSTEM(BMS) OVERVIEW

The Battery Management System (BMS) in one sentence, can be described as a system that monitors and controls battery state and performance. It is like a controlling module or the master module for the lithium-ion battery pack of the electric vehicle, which maintains the overall health of the battery pack. The purpose of the Battery Management System is to make sure the safe operation of the battery by keeping the battery within its Safe Operating Range thus keeping the battery pack healthy and extending it lifespan.

The BMS performs several critical functions, which can be broadly categorized as follows:

- Monitoring and Data Acquisition:

In BMS the parameters like cell voltages, overall pack voltage, charge and discharge current, state of charge, state of health and temperatures are continuously measured using sensors. These measurements are used to identify the battery's conditions and detect any abnormal operations in real time.

- State Estimation:

Because there is no way to measure the conditions within the battery directly, the BMS uses estimation techniques like algorithms to find out information about things like SOC (State of charge), SOH (State of health), and SOP. These pieces of information help us understand things about the energy storage capabilities, degradation state, and power capabilities of the battery pack.

- Battery Protection:

The BMS provides functions which are protective that are designed to safeguard against undesirable operating states of the battery like battery being overcharged or uncharged. BMS provide protective functions that include protection from over-voltage, under-voltage, over-current, short circuit, and high/low temperatures, thus avoiding situations like thermal run- away and physical damage to battery.

- Cell Balancing:

Cell imbalance arises due to manufacturing variations, temperature gradients, and aging effects. To address this, the BMS employs balancing techniques. Passive balancing dissipates the surplus energy mainly in the form of heat through resistors, while active cell balancing involves the transfer of energy from one cell to another through capacitors or inductors.

Overall, the BMS plays a vital role in enhancing battery safety, reliability, and lifespan. Among its various functions, effective cell balancing is particularly critical for maximizing usable capacity and ensuring long term performance of lithium-ion battery systems.

A.Cell Balancing Topologies

Cell balancing techniques are employed within the Battery Management System (BMS) to maintain a uniform SOC across all cells that are present in a battery pack. Proper balancing im- proves battery lifespan, enhances safety, and ensures efficient energy utilization, as shown in Fig. 2. [1] An overview of the different cell balancing techniques is illustrated in Fig. 1.

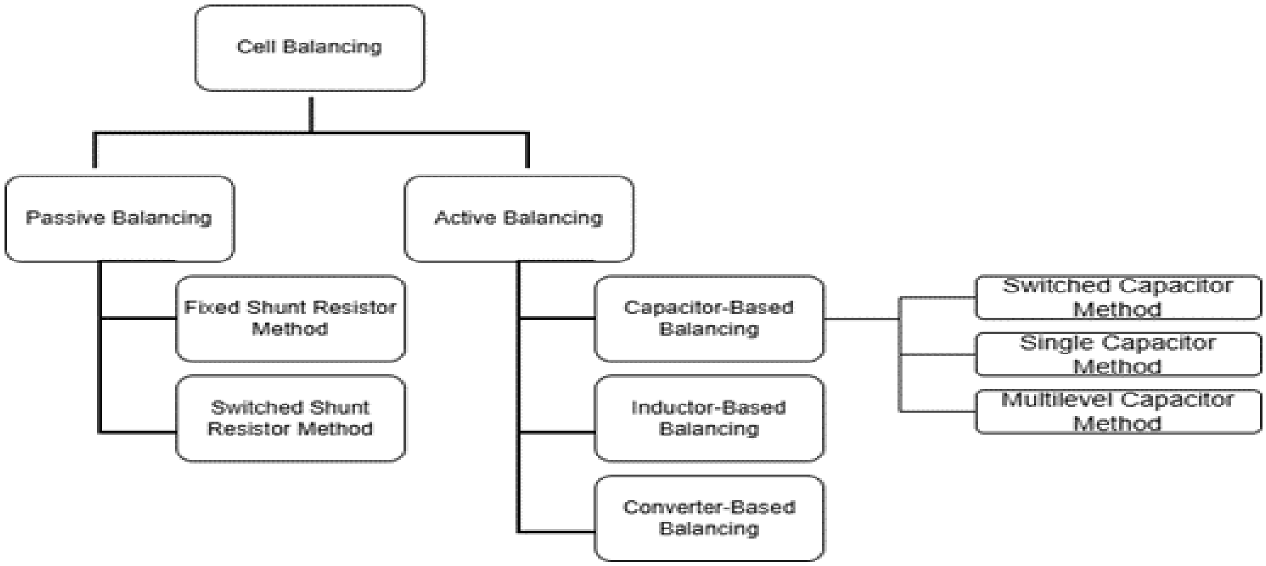

Fig. 1. Types of cells balancing methods including passive and active methods

1) Passive Cell Balancing:

Passive cell balancing equalizes cell voltages by dissipating or dispersing excess energy from the highly or highest charged cells as heat using resistive elements connected across individual cells. This approach is widely used as its simply and ease of implementation [2]– [4].

The key advantages of passive balancing include:

- Simple implementation
- Low cost
- Minimal control complexity

However, passive balancing suffers from energy loss in the form of heat, resulting in reduced overall system efficiency.

a) *Fixed Shunt Resistor Method:*

In this fixed shunt resistor method, each cell is connected to a resistor that continuously bleeds excess charge. This approach prevents overcharging and requires minimal control.

- Simple hardware design
- No complex control required

The primary drawback is continuous power dissipation, leading to thermal losses and poor efficiency in high- performance applications.

b) *Switched Shunt Resistor Method:*

This method im- proves upon the fixed resistor approach by activating resistors only when required using switches such as MOSFETs or relays.

- Controlled balancing based on cell voltage
- Reduced unnecessary power loss

Despite improvements, energy is still dissipated as heat, and additional thermal management is required. This method is typically suitable for low-power systems.

2) Active Cell Balancing:

Active balancing techniques re- distribute energy between cells instead of dissipating it. Energy is transferred from cells which has highest SoC to cells which has lower SoC using energy storage elements and power electronic circuits [5], [6].

The advantages of active balancing include:

- High energy efficiency
- Improved battery utilization
- Extended battery lifespan

However, these methods involve higher circuit complexity and require advanced control algorithms.

Active balancing techniques can be broadly classified into capacitor based, inductor based, and converter-based methods.

a) Capacitor-Based Balancing:

Capacitor-based methods use capacitors to temporarily store and transfer energy between cells.

Switched Capacitor Method:

Energy is transferred sequentially between adjacent cells using multiple capacitors and switches.

- Moderate efficiency
- Simple control strategy

Limitations include slower balancing speed and increased component count.

Single Capacitor Method:

This approach uses a single capacitor with multiple switches.

- Reduced component count
- Cost-effective for larger systems

However, balancing speed depends on switching strategy and control design.

Multi-Level Capacitor Method:

Multiple capacitor layers are used to improve energy transfer paths.

- Faster balancing
- Improved energy transfer capability

This comes at the cost of increased circuit complexity.

b) Inductor-Based Balancing:

Inductor based active balancing method use the inductor or transformers to transfer energy between cells instead of bleeding the excess energy. These methods enable controlled energy transfer and support higher balancing currents and thus does not waste any energy or the voltage of the cell.

- Faster balancing compared to capacitive methods
- Suitable for high-power applications

However, this type of balancing requires high frequency switching and involves magnetic losses, thereby increasing design complexity and cost.

c) Converter-Based Balancing:

Converter based active balancing employs DC-DC converters to efficiently redistribute energy across cells among the battery pack.

Common type of converter topologies include:

- Buck-Boost converters
- Flyback converters
- Buck converters
- Full-bridge converters

These methods offer high efficiency and flexibility but require sophisticated control and higher implementation cost.

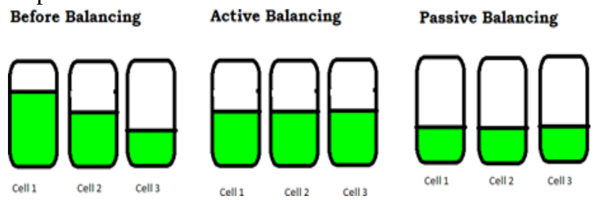

Fig. 2. Comparison of battery conditions before balancing and after applying passive and active cell balancing techniques

III. PROPOSED HYBRID CELL BALANCING SYSTEM

The proposed hybrid balancing system combines passive and active techniques to achieve an effective trade-off among cost, energy efficiency, and balancing speed [1].

A. Passive Cell Balancing: Switched Shunt Resistor Topology

The switched shunt resistor type of passive balancing is used in the proposed system due to its simplicity and less cost [2], [3]. In this type of configuration, a resistor is connected across each cell through a controllable switch (usually MOSFET). This helps in dissipating the excess energy from more charged SOC cells. Compared to the fixed resistor topology, this topology guarantees less energy dissipation by active devices only when necessary. And as only a MOSFET and resistor is used, this reduces the cost. And the control logic is realized with simple algorithm based on threshold. However, because excess energy is dissipated in form of heat, this method is most suitable for correcting minor imbalances or for fine balancing during the final stages of equalization.

B. Active Cell Balancing (Inductor-Based Topology)

For active balancing, an inductor-based topology is employed to enable efficient energy transfer from cells which has higher SoC to cells which has lower SoC [5], [6]. The circuit utilizes inductors along with controlled switches to store and redirect energy rather than dissipate it.

This method supports higher balancing currents, which significantly reduces equalization time. It offers improved energy utilization and scalability for battery packs containing a large number of cells. Nevertheless, the inclusion of inductors and high-frequency switching increases circuit complexity, introduces magnetic losses, and raises component costs relative to passive approaches [7] [8] [9].

C. Control Algorithm

The proposed control algorithm will continuously monitor the State of charge i.e., SOC of each cell and selects the appropriate balancing mode according to the magnitude of State of charge i.e., SOC deviation.
In the case of small SOC difference of the cells, algorithm works in switched shunt resistor (passive) mode, preventing un-necessary switching losses and complexity. The Inductor based Active Balancing Algorithm will be used when the SOC (State of Charge) differencing exceeds a certain limit.
Due to this adaptability, the overall BMS energy loss shall be less, it will accelerate the balancing and enhance efficiency and reliability.

The overall control algorithm of the proposed hybrid cell balancing system is shown in Fig. 3.
As shown in Fig. 3, the control algorithm begins by measuring the State of charge i.e., SOC of each cell. The next step is checking the state of charge SOH between the cells. When there is a lesser SoC difference the passive balancing technique is activated which makes use of a switch shunt resistor which wastes additional energy If not, the selection of inductor-based active balancing method must be done for transferring energy between cells.

IV. SYSTEM MODELING AND SIMULATION

MATLAB Simulink was used to simulate the proposed hybrid cell balancing method to ensure its performance under varying operating conditions with regard to design and modeling. The system consists of two cells of lithium-ion battery whose equivalent electrical model along with blocks for state of charge estimation of the battery cells. The state of charge (SOC) and voltage of the individual cells are consistently monitored and relayed to a central control unit. The centralized control unit determines which balance strategy should be applied at instant on real time basis depending on the SOC and voltage of each battery cell.

The overall system model is composed of the following key components:

- Battery cell models, including SOC estimation
- Voltage sensing blocks
- Current sensing block
- Control logic unit for decision-making

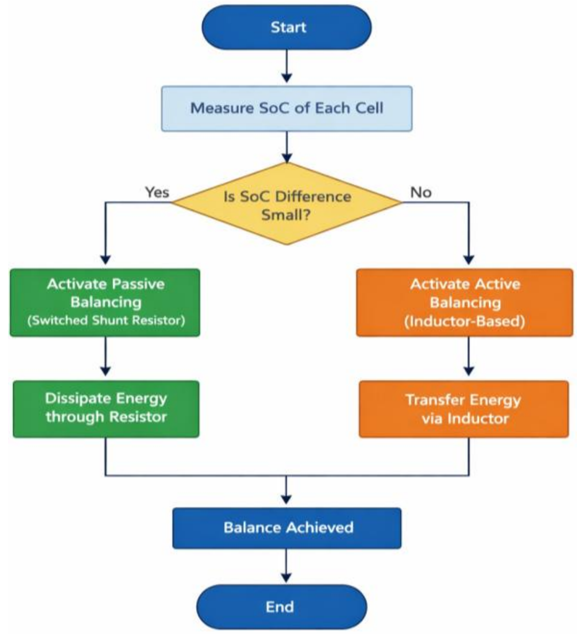

Fig. 3. The flowchart of proposed hybrid cell balancing control algorithm

The balancing circuit integrates both passive and active balancing paths within a single framework. The passive path consists of resistors connected across each cell through con- trolled switches, enabling selective discharge of excess energy. The active path employs an inductor-based energy transfer mechanism along with switching elements to facilitate efficient energy redistribution between cells.
As shown in Fig. 3, the operation of the system is governed by the difference in SOC between the cells. A threshold value is defined to distinguish between large and small imbalance conditions. Based on this comparison, the system dynamically switches between two operating modes.

1) Active Balancing Mode (High SOC Difference):
The active balancing circuit implementation is shown in Fig. 4. When the SOC difference exceeds the predefined threshold, the system operates in active balancing mode. In this mode, the energy is transferred from the cell which has higher SoC to cell which has lower cell using an inductor-based energy transfer path. This method employs an inductor, which draws

energy away from a battery and stores it under control when necessary. The inductor subsequently allocates energy back to the right cell as necessary under regulation. Most importantly, cells cannot directly transfer energy, as energy will interchange between the inductor to their respective cell. The operational circuitry has energy storage.

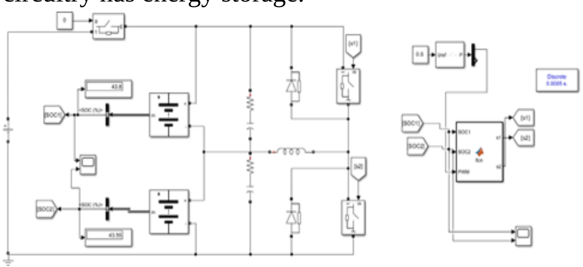

Fig. 4. Inductor based active balancing circuit used for energy transfer between cells.

2) Passive Balancing Mode (Low SOC Difference): The passive balancing circuit implementation is shown in Fig. 5. The system will switch to passive balancing mode if the difference in state-of-charge exceeds a predefined threshold parameter. The threshold parameter here is represented by the coefficient k. In this mode, the extra energy from the higher SOC cell gets wasted through the resistive path. Additional functioning in this manner refers to switching on the resistor branch of the high SOC cell and dissipating the added energy as heat. This approach, while leading to energy loss, remains effective for nearly balanced cells due to its precision in achieving balance.

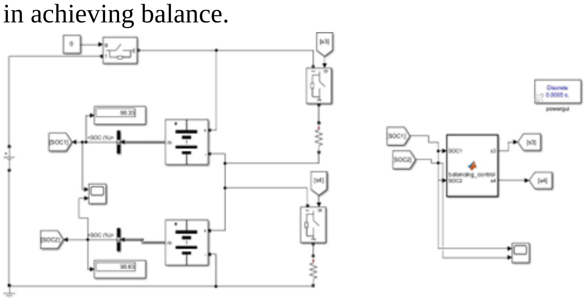

Fig. 5. Resistive passive cell balancing circuit used for dissipating excess energy.

Taking the SOC values of the battery cells as unequal simulate imbalance conditions that exist in real life. The algorithm tracks the SOC values continuously. As the SOC difference varies continuously, the controller switches between active and passive operation.

The key simulation parameters considered include:

- Initial SOC mismatch between cells
- Threshold value for mode switching
- Switching behavior of the balancing circuit

The detailed implementation of the proposed hybrid balancing circuit, including both active and passive paths along with the control switches, is illustrated in Fig. 6.

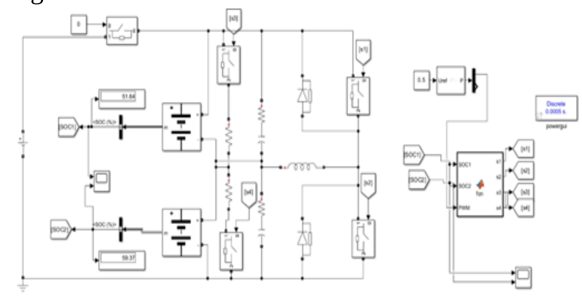

Fig. 6. The proposed hybrid cell balancing circuit Simulink model showing both active and passive balancing paths.

V. RESULTS AND ANALYSIS

Simulation results of active circuit as shown in Fig. 7and passive circuit as shown in Fig. 8

A. Balancing Circuit Behavior

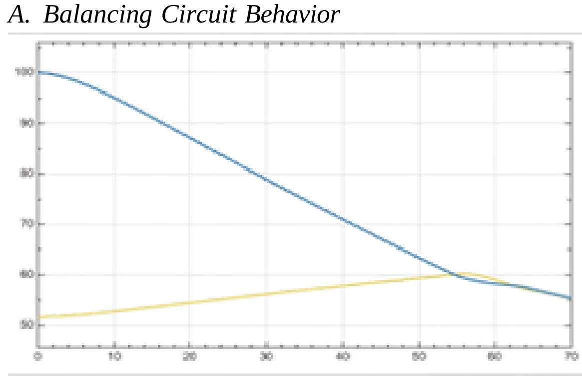

Fig. 7. Active balancing waveform.

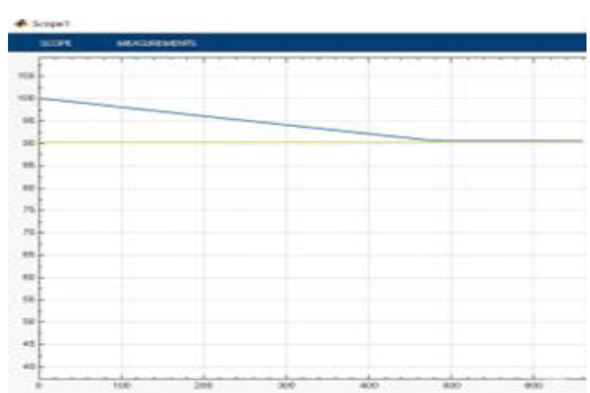

Fig. 8. Passive balancing waveform.

Simulation results show that the hybrid balancing system improves overall battery performance. The control algorithm effectively switches between passive and active balancing modes depending on the voltage difference between cells.

VI. RESULTS AND ANALYSIS

A. Case 1: High SOC Difference (Active Balancing)

The performance of the proposed hybrid balancing system under high initial SOC mismatch is illustrated in Fig. 9. The initial SoC difference between the two cells is approximately 50%, representing a severe imbalance condition.

It can be observed that the SOC of the higher-charged cell decreases rapidly, while the SOC of the lower-charged cell increases correspondingly. This indicates that the system operates in active balancing mode, where the energy is efficiently transferred from one cell to another through the inductor-based path. The Threshold set for the controller to activate Active Cell balancing is set for about 15% of the difference of SoC.

Compared to passive balancing, the equalization process is significantly faster and more energy-efficient, as minimal energy is dissipated as heat. The convergence of SOC values demonstrates the effectiveness of active balancing in handling large imbalance conditions. In this work, SOC differences below 5% are neglected, as such small variations have minimal impact on overall system performance and do not justify active balancing intervention.

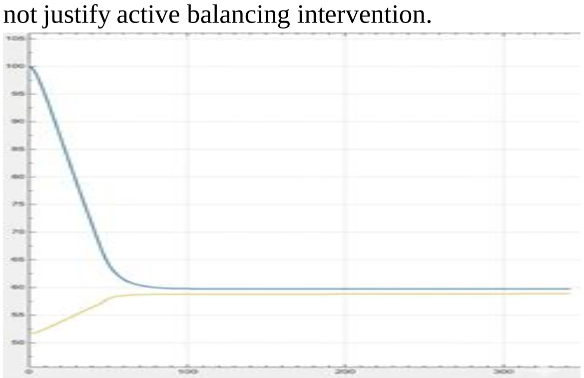

Fig. 9. SOC equalization under high initial imbalance (50%) using active balancing in the hybrid circuit. (Idel State)

B. Case 2: Low SOC Difference (Passive Balancing)

The system behavior under low SOC mismatch is shown in Fig. 10, where the initial imbalance is approximately 7%.

In this case, the SOC of the higher-charged cell gradually decreases until both cells reach equilibrium. Since the imbalance is small, the system operates in passive balancing mode, where excess energy is dissipated through resistive elements.

Although this method results in energy loss, it provides finer control and avoids the complexity of active balancing circuits. The smooth convergence indicates stable operation and accurate balancing for near-equal SOC conditions.

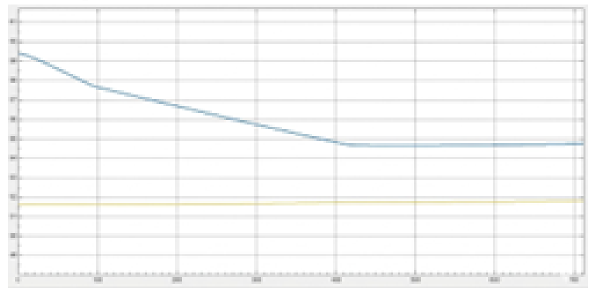

Fig. 10. SOC equalization under low initial imbalance (7%) using passive balancing in the hybrid circuit. (Idel State)

The overall charging behavior of the proposed hybrid balancing circuit is illustrated in Fig. 11, which depicts the combined effect of active and passive balancing during operation.

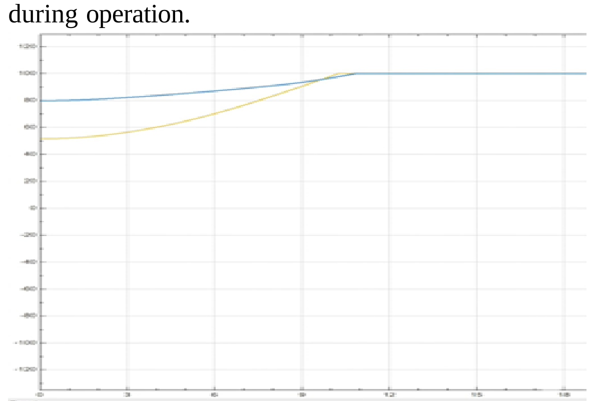

Fig. 11. Charging output response of the proposed hybrid cell balancing circuit.

Compared to conventional passive balancing methods, the proposed hybrid approach reduces the settling time for voltage equalization by approximately 20%. In addition, energy loss and heat dissipation are reduced due to the implementation of active balancing.

These improvements tangibly enhance the efficiency of the BMS and contribute to increased lifespan and the reliability of Li-ion battery packs used in electric vehicles.

VII. CONCLUSION

In this paper, we present and try to prove that a hybrid balancing system incorporating both active type and passive type of balancing is practical. The researchers also propose a sophisticated cell selection strategy. The dynamic cell selection voltage threshold is based on the difference between the SoC of each cell. Making use of a dynamic cell selection voltage threshold, the hybrid energy balancing algorithm can dynamically select from the more suitable balancing between.

Moreover, AC Passive Cell Balancing helps achieve optimized equalization of smaller SoC differences along with a reduced control complexity. Particularly, a minimum SOC threshold of 5% improves system efficiency by eliminating needless switching operations. The outcomes of the simulations proved that due to its quick charge redistribution and energetic cells-takeover capabilities the active balancing mode is suited to large SOCs.

The hybrid approach is a good compromise between speed and efficiency and complexity of implementation. As a result, the battery's life span and overall functionality of the system improves. The methodology offers more efficient or equal performance when compared with conventional one mode balancing techniques in terms of their flexibility and energy consumption, as the results show.

In addition, the conclusion emphasizes the hardware implementation and validation of the proposed system for real-time operation, while the future scope includes optimization of control algorithms for large-scale battery management systems. It has also been noticed that for as.

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