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DESIGN OF FUZZY LOGIC CONTROLLER FOR INDUCTOR BASED ACTIVE CELL BALANCING IN THE BATTERY MANAGEMENT SYSTEM

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ABSTRACT

In recent years, the use of petroleum products such as petrol and diesel has decreased due to the introduction of electric vehicles, and batteries have become the main component of EVs. Lithium-ion batteries are mostly used because of their smaller size and higher capacity. However, cell imbalance occurs in a battery pack due to several internal and external factors, which affect the charging and discharging process and the state of charge of individual cells. To overcome this problem, battery management systems use different balancing techniques.Cell imbalance can be reduced either by passive cell balancing, where excess energy is dissipated in the form of heat, or by active cell balancing, where energy is transferred from the cell having higher energy to the cell with lower energy. This paper presents an inductor-based active cell balancing technique, which is known for its high rate of energy transfer. Fuzzy logic is implemented to drive the duty cycle of PWM switching signals for controlling the balancing operation.

In this paper, the performance of the system is compared with and without fuzzy logic by observing the state of charge balancing of the cells during charging and discharging. A simulation model consisting of four battery cells connected in series is used for analysis. The balancing technique with fuzzy logic provides a more uniform state of charge distribution under the given initial conditions compared to the system without fuzzy logic.

Keywords: Battery Management System, Active Cell Balancing, State of Charge, Fuzzy Logic Controller, Lithium-ion Battery, Electric Vehicle

Introduction

The use of electric vehicles is increasing day by day due to their high efficiency and zero carbon emission compared to gasoline-based vehicles. Electric vehicles use a battery and motor to operate, where the battery is the most critical element of the entire EV system. The growing demand for electric vehicles has been made possible due to advancements in battery technology.
There are different battery chemistries available for energy storage, such as Nickel–Cadmium (Ni-Cd), Lithium Cobalt Oxide (LCO), Lithium Manganese Oxide (LMO), and Lithium-ion batteries. Among these, lithium-ion batteries are widely used due to their compact design, high energy density, better efficiency, and reliability. A single battery cell generally has a nominal voltage in the range of 2.5 to 3.7 V and by combining multiple cells in series and parallel the required voltage and capacity of the battery pack is meet.[1][7]

When a large number of battery cells are connected together, imbalance among the cells becomes a major issue. This imbalance occurs due to factors such as manufacturing variation, aging effects, environmental conditions, and different operating conditions. As a result, differences appear in state of charge, voltage, temperature, and self-discharge rate of the cells, which reduce the overall performance, safety, and lifetime of the battery pack. In order to overcome these problems, a Battery Management System (BMS) is used to monitor and control individual cells. Cell balancing techniques are generally classified into passive and active balancing methods. Passive balancing dissipates excess energy in the form of heat and is inefficient for high-capacity battery systems.[2][3]

Active cell balancing transfers energy from cells with higher energy to cells with lower energy. Capacitor-based balancing methods are faster but require complex circuitry. Inductor-based balancing methods are comparatively slower; however, they are simple, efficient, and provide controlled energy transfer with minimal error and minimal energy loss, making them suitable for practical battery management applications. In this work, fuzzy logic is used as a control technique to improve the balancing process. Instead of relying on exact mathematical models, fuzzy logic uses rule-based decision making, which helps in handling non-linear behavior and uncertainties present in battery parameters. By applying fuzzy logic, the balancing operation becomes smoother and more adaptive under different operating conditions, improving the overall effectiveness of the active cell balancing system.[4][5][6]

Schematic Diagram

Figure 3.7 shows the schematic diagram of a battery cell balancing circuit that uses a single inductor to transfer energy from a higher-energy battery cell to a lower-energy battery cell. The balancing circuit operates in two main phases. In the first phase, energy from the higher charged battery cell is used to charge the inductor by turning ON the corresponding control switches. For example, when Battery 1 has higher energy than Battery 3, the switches connected to Battery 1 are turned ON, allowing current to flow through the inductor and store energy in its magnetic field.In the second phase, the control switches are adjusted so that the inductor is connected to the lower-energy cell, in this case Battery 3. The inductor then discharges and transfers the stored energy to Battery 3, thereby helping to equalize the charge levels between the cells. This entire operation is controlled using switching actions and duty cycles, which determine how long each switch remains ON or OFF during the balancing process.

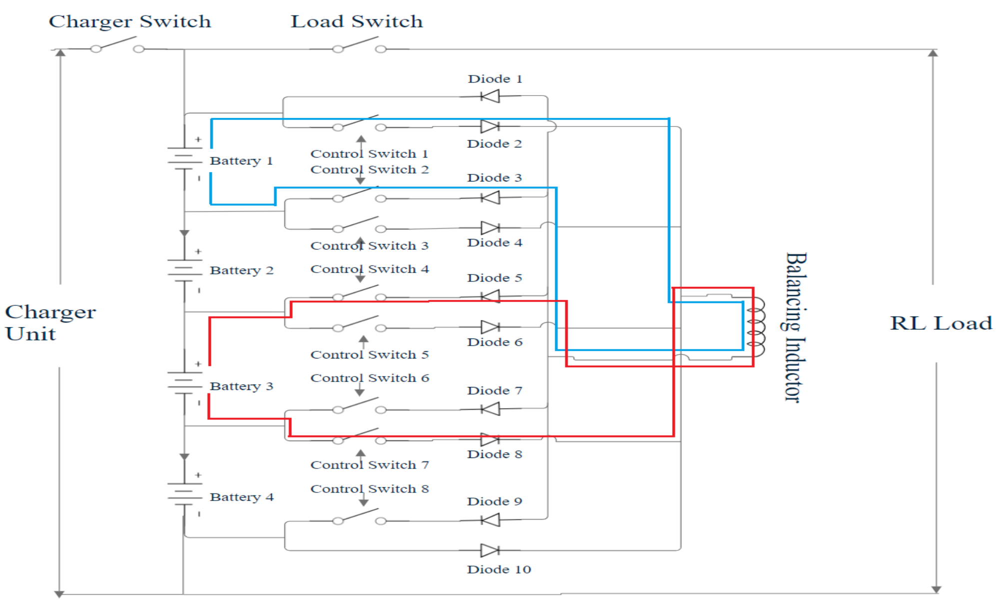

Figure 1:Schematic diagram of balancing circuit

Diodes are placed in the circuit to ensure current flows in the correct direction and to prevent reverse current, which could damage component or disrupt the energy flow.

The highlighted paths in the figure (blue and red lines) represent the energy flow from Battery 1 to Battery 3, demonstrating how the inductor plays a central role in redistributing energy between cells. This method is widely used in battery management systems to enhance efficiency, safety, and the overall lifespan of multi-cell battery packs.

Flow chart

The flowchart describes the design of Fuzzy logic controller for Inductor based Active Cell Balancing and Charging/Discharging Management System for battery cells using single inductor.

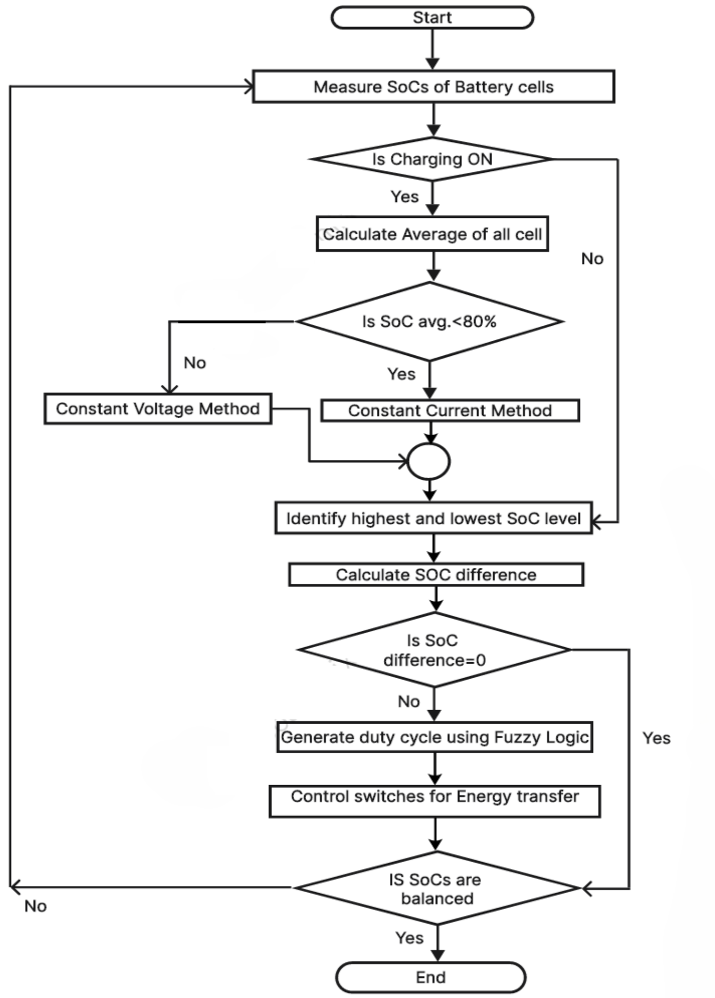

Figure 2 : Flowchart of design of fuzzy logic controller for cell balancing in the battery management system

At first, the State of Charge (SOC) of all battery cells are measured. If charging is ON, the system first computes the average SOC of all four cells. Based on this, if the average SOC is below 80%, the system applies Constant Current (CC) Charging; if not, it switches to Constant Voltage (CV) Charging. Next, the system identifies the highest and lowest SOC levels among the cells and calculates the SOC difference as well as SoC average of two cells. If the SOC difference is zero, balancing is skipped, and the process loops back to SOC measurement. Otherwise, the fuzzy logic controller generates a duty cycle based on the SOC difference and the average SOC. This duty cycle is then used to control PWM-based switches that facilitate energy transfer from the highest SOC cell to the lowest SOC cell using a single inductor. The system continuously checks if the SOC levels are balanced; if not, it repeats the balancing process. If the SOC difference falls below a defined threshold, the system loops back to SOC measurement. The process ensures efficient energy management among battery cells to maintain balanced SOC levels. Additionally, if discharging is ON, energy is discharged through a resistor and inductor load, ensuring controlled discharging.

Fuzzy Rule Table

The Mamdani fuzzy rule table is formulated based on the following principles:

1. If there is a significant SOC difference, a large duty cycle is required to increase the balancing current.
2. If the average SOC is high, and the SOC difference is also high, a large duty cycle is applied to ensure a significant balancing current.
3. If both the SOC average and difference are low, a small duty cycle is applied to reduce the balancing current.
4. If both the SOC average and difference are moderate, a medium duty cycle is applied to maintain a moderate balancing current.

Rules	**VL**	**L**	**M**	**H**
L	L	ML	M	MH
M	ML	M	M	MH
H	M	MH	MH	H
VH	MH	H	H	H

Table 1: Fuzzy Table Rules

MATLAB Simulink Model

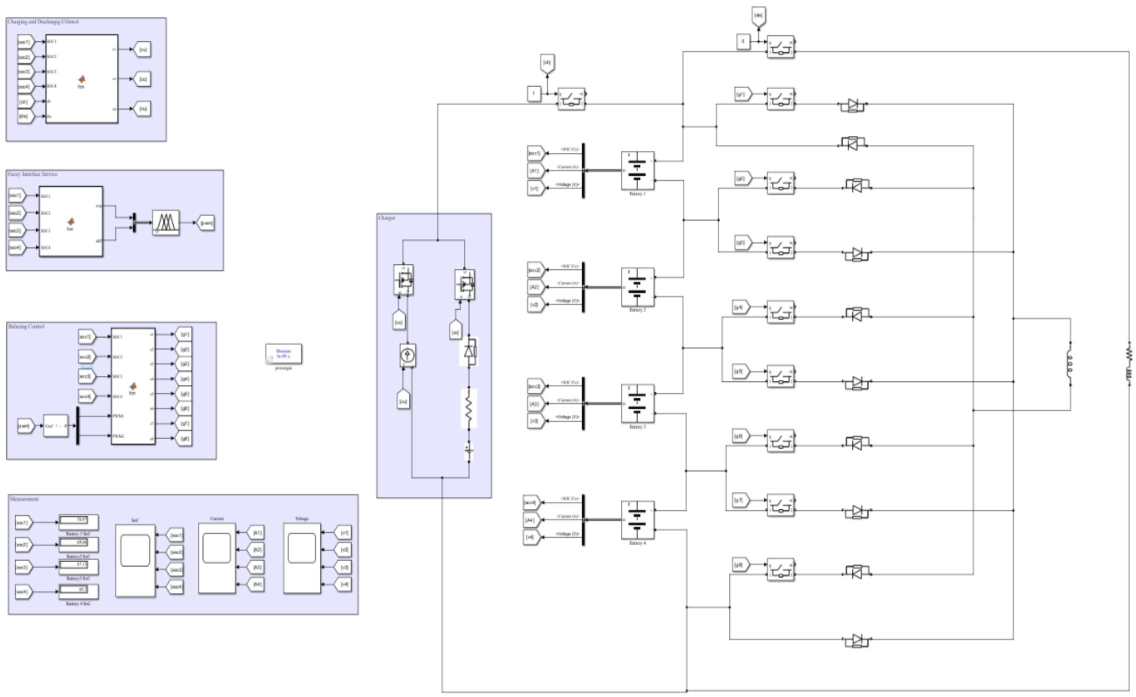

Figure 3:Simulation setup in MATLAB/Simulink

The simulation setup focuses on implementing active cell balancing for four series-connected batteries using fuzzy logic to control the duty cycle.

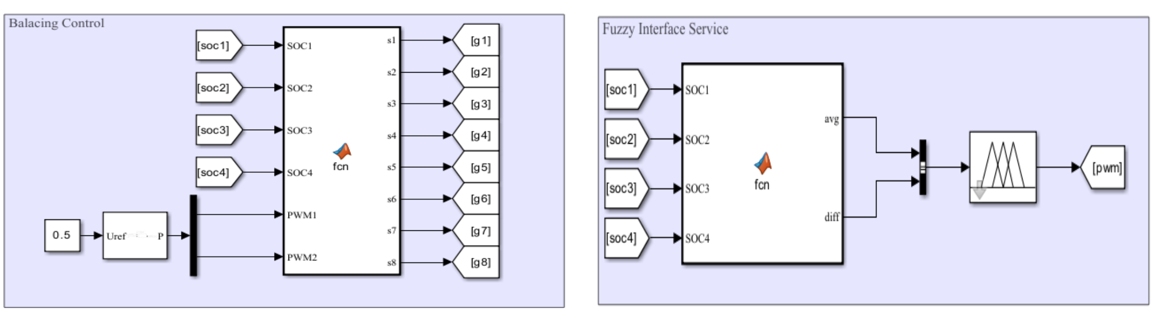

Figure 4: Balancing control and Fuzzy interface

The balancing control compares the SoC levels of the batteries and identifies the maximum and minimum SoC levels. The difference and the average of SoC level of these batteries are given as crisp inputs to the Fuzzy Interface Service. Based on the difference and average of SoC level of batteries, the Fuzzy logic controller converts crisp inputs into fuzzy input data. Based on the fuzzy rules, Fuzzy logic controller gives fuzzy output data. Now the De-fuzzifier converts that output into real world crisp values. These values are used as duty cycle for our system.

The batteries are modeled in Simulink with initial SOC imbalances to simulate real-world scenarios. The charging process begins with Constant Current (CC) mode, where a fixed current is applied until the SOC reaches 80%. Beyond 80%, the system transitions to Constant Voltage (CV) mode, maintaining a constant voltage as the current gradually decreases. A fuzzy logic controller (FLC) is used to determine the duty cycle for the balancing circuit based on the SOC difference and average SOC of the four batteries. The balancing circuit, consisting of a single shared inductor and combination of switch and diode, transfers energy from the higher SOC battery to the lower SOC battery. The FLC dynamically generates gate signals for the switches based on the SOC conditions to minimize the imbalance. The simulation tracks SOC levels, charging profiles, and balancing currents to validate the system's performance, ensuring efficient energy transfer and safe battery operation during both CC and CV phases.

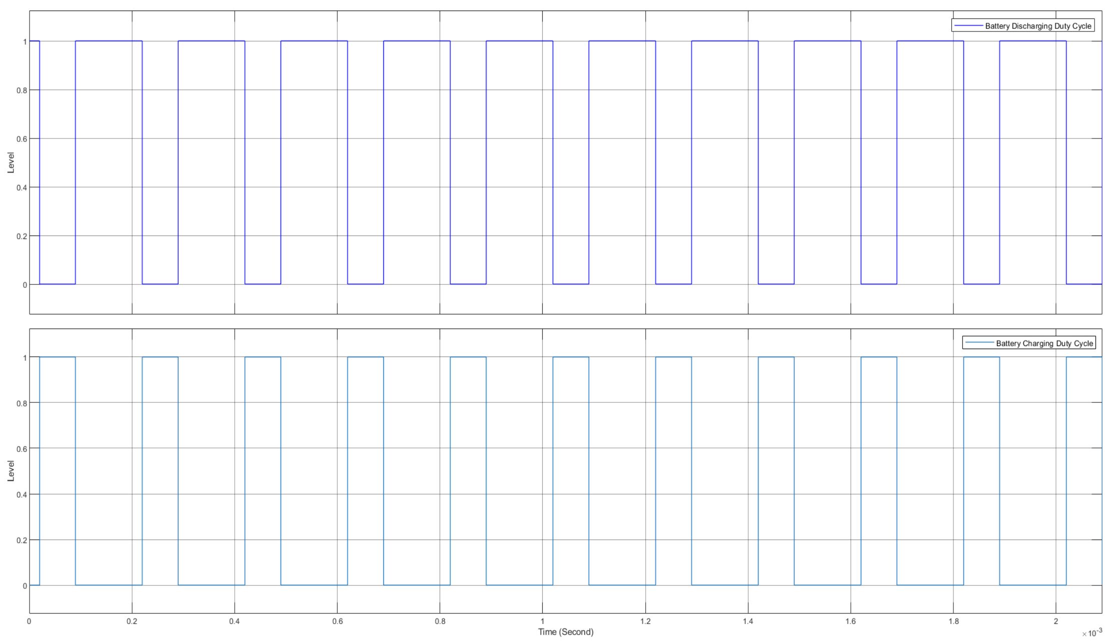

Figure 5: Duty Cycle

RESULT AND DISCUSSION

4.1 Simulation Results

After the simulation of the model in MATLAB/Simulink software, the output as follows:

i. Charging SOC without Fuzzy logic control

This graph shows the active cell balancing during charging without using FLC. The batteries have reached equal SoC after 33 seconds and at 66.1%.

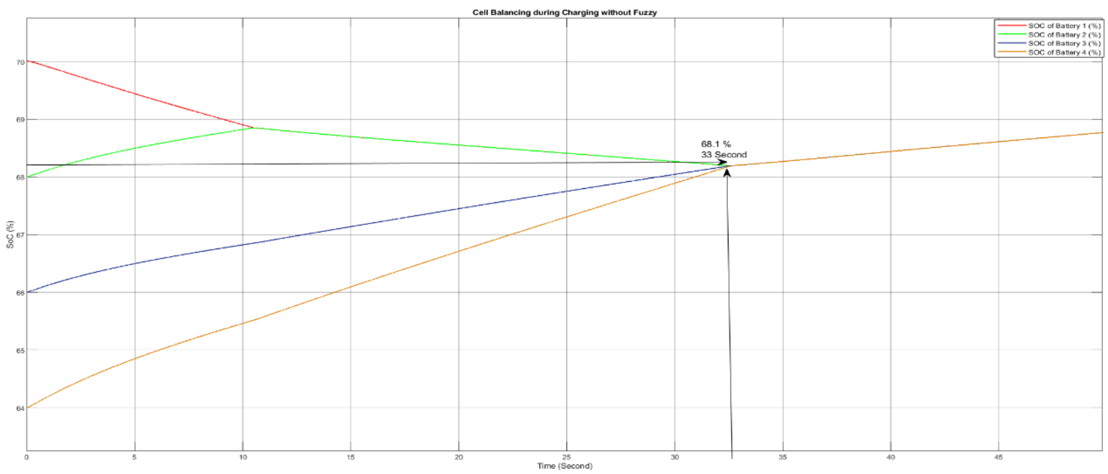

Figure 6: Charging SoC without FLC

ii. Discharging SOC without Fuzzy logic control

This graph shows the active cell balancing during discharging without using FLC. The batteries have reached equal SoC after 45.5 seconds and at 65.6%.

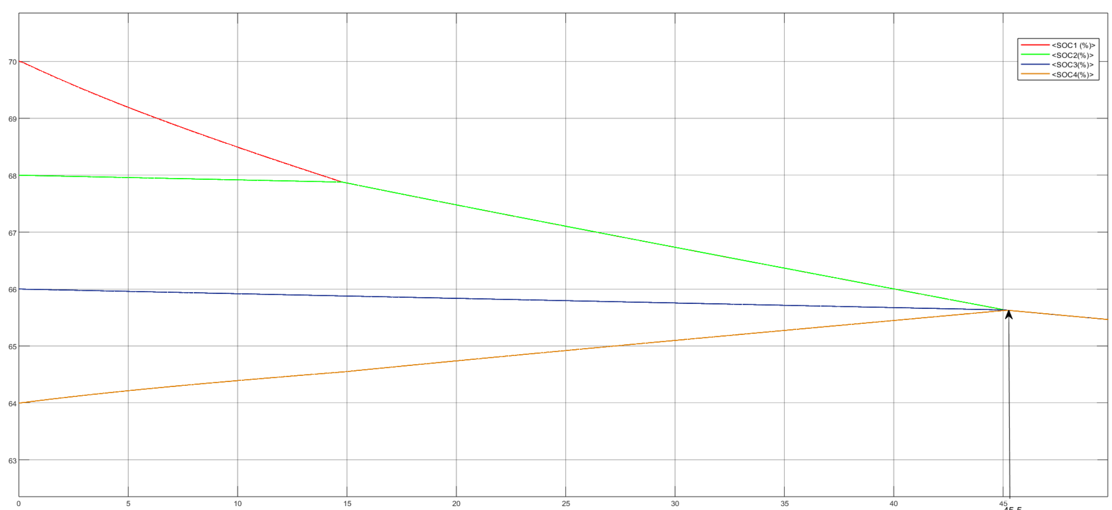

Figure 7: Discharging SoC without FLC

iii. Charging current without Fuzzy logic control

Chart shows the charging current without Fuzzy logic controller for each of the four batteries used in the simulation. This chart shows the respective response of each battery during charging to meet at a point.

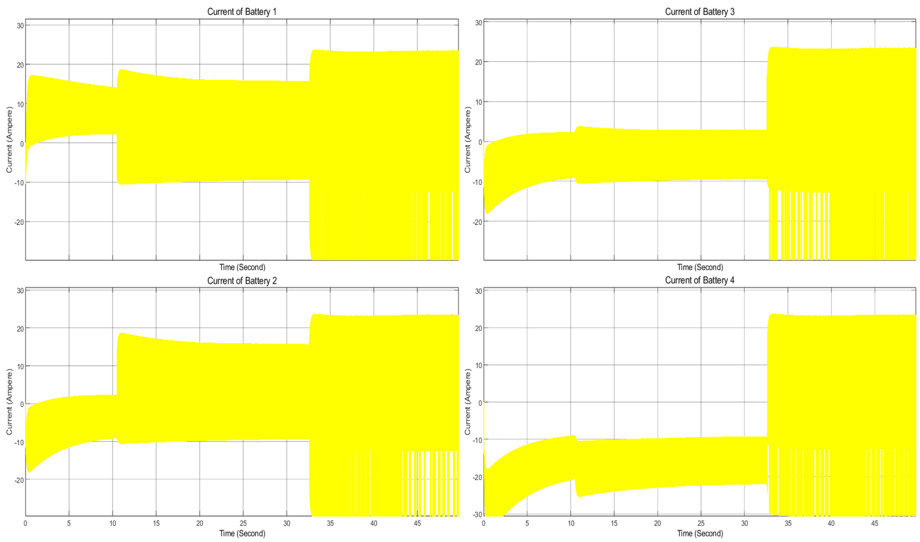

Figure 8: Charging current without FLC

iv. Discharging current without Fuzzy logic control

Chart shows the discharging current without Fuzzy logic controller for each of the four batteries used in the simulation. This chart shows the respective response of each battery during discharging to meet at a point.

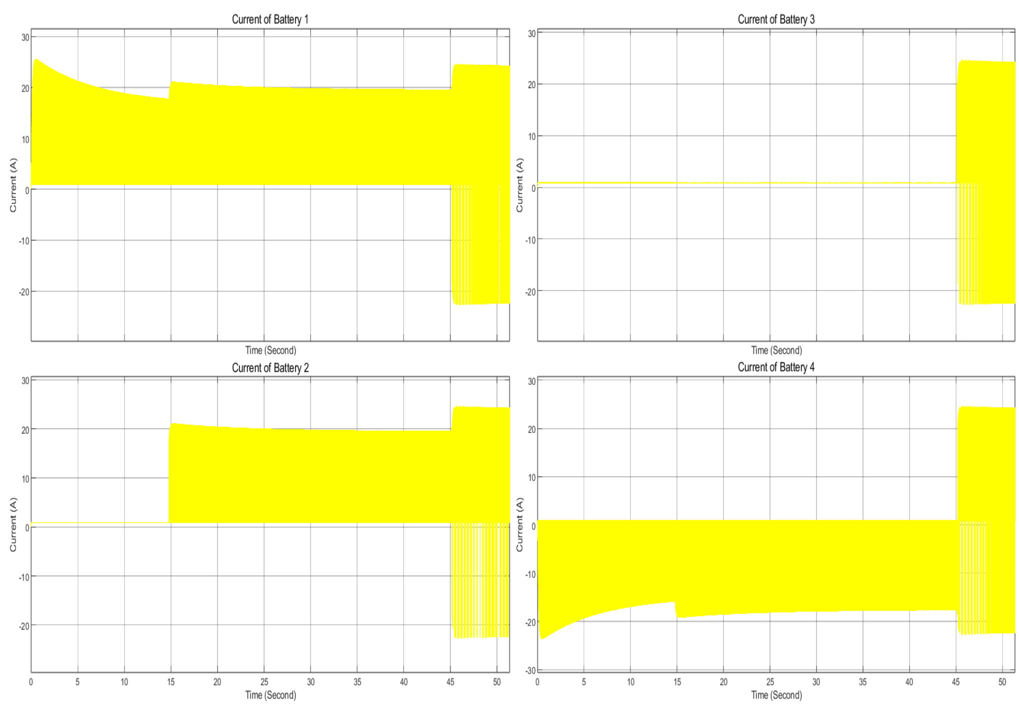

Figure 9: Discharging current without FLC

v. Charging voltage without Fuzzy logic control

Chart shows the charging voltage without Fuzzy logic controller for each of the four batteries used in the simulation. This chart shows the respective response of each battery during charging to meet at a point.

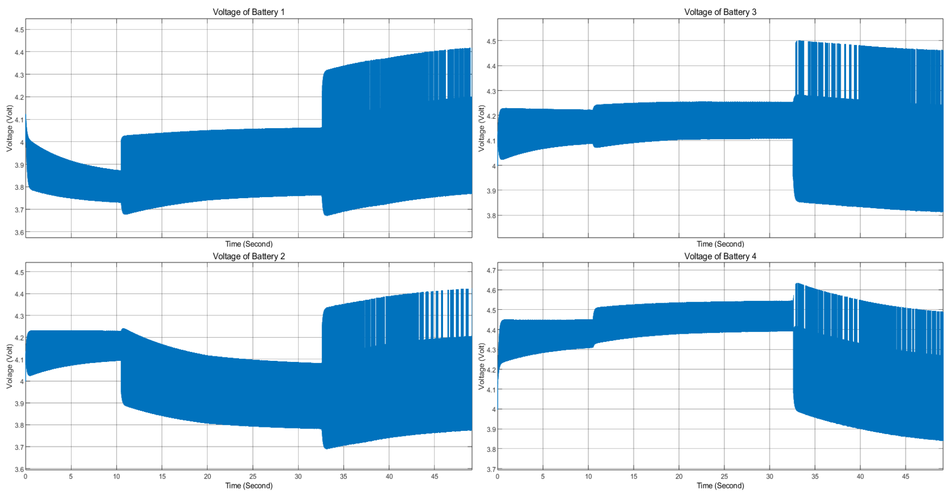

Figure 10: Charging voltage without FLC

vi. Discharging voltage without Fuzzy logic control

Chart shows the charging voltage without Fuzzy logic controller for each of the four batteries used in the simulation. This chart shows the respective response of each battery during discharging to meet at a point.

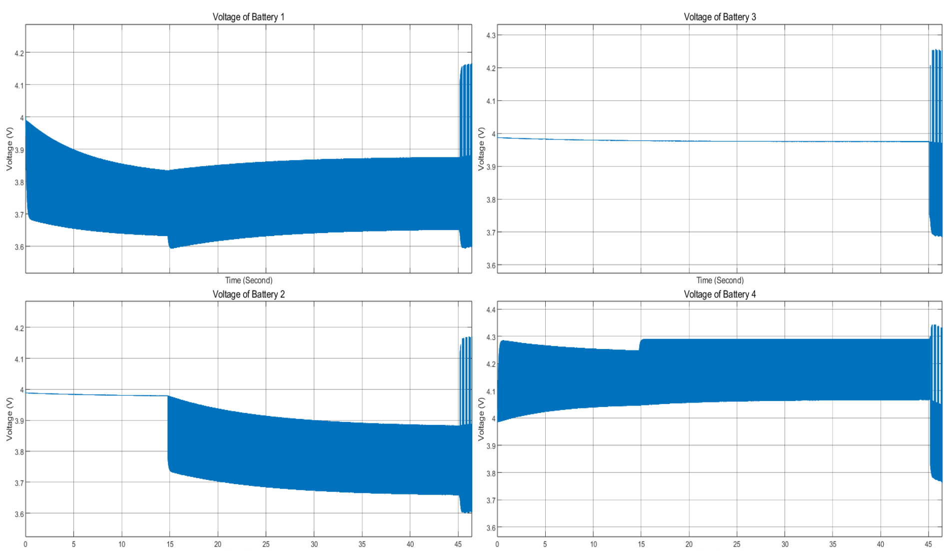

Figure 11: Discharging voltage without FLC

After the results obtained without Fuzzy logic control, the system was operated with using Fuzzy logic control and the following results are obtained:

i. Charging SOC with Fuzzy logic control

This graph shows the active cell balancing during charging with using FLC. The batteries have reached equal SoC after 34.7 seconds and at 69.2%.

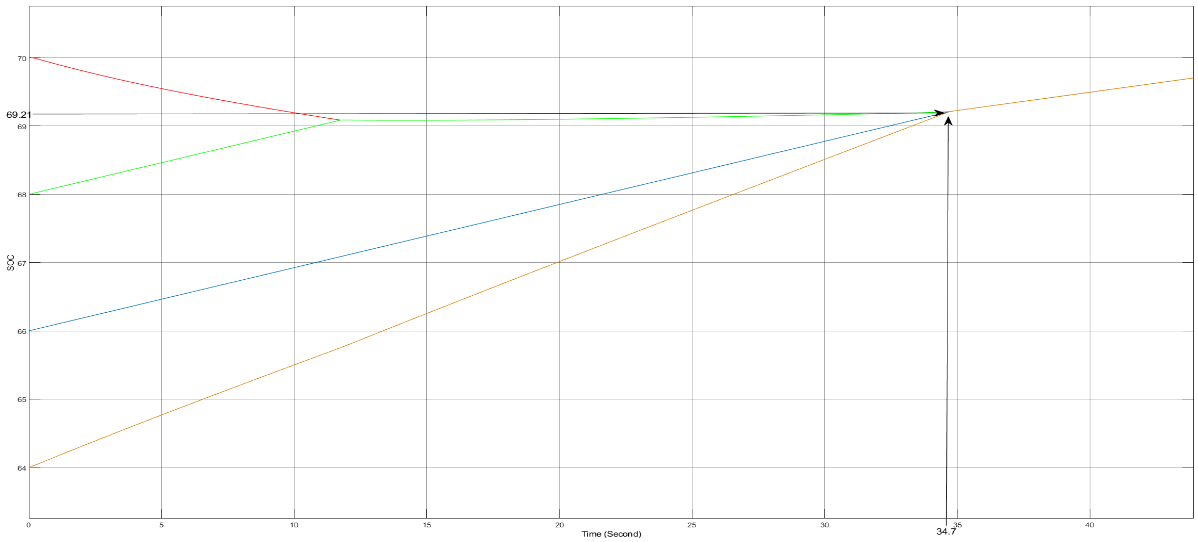

Figure 12: Charging SoC with FLC

ii. Discharging SOC with Fuzzy logic control

This graph shows the active cell balancing during discharging with using FLC. The batteries have reached equal SoC after 45.2 seconds and at 65.55%

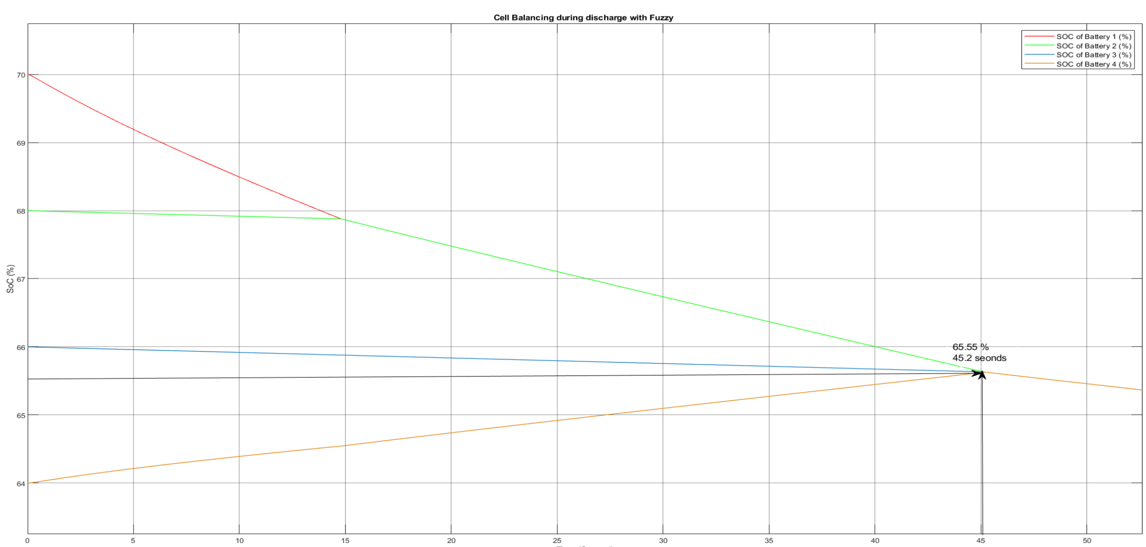

Figure 13: Discharging SoC with FLC

iii. Charging current with Fuzzy logic control

Chart shows the charging current with Fuzzy logic controller for each of the four batteries used in the simulation. This chart shows the respective response of each battery during charging to meet at a point.

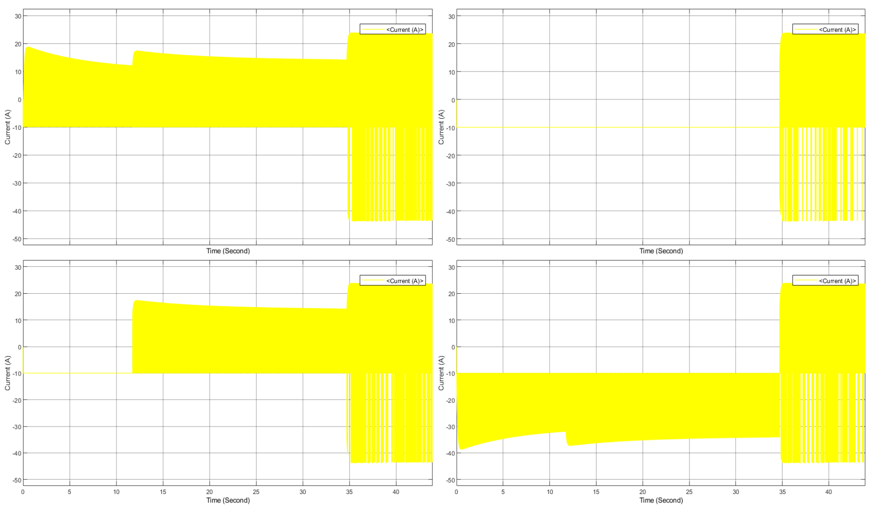

Figure 14: Charging current with FLC

iv. Discharging current with Fuzzy logic control

Chart shows the discharging current with Fuzzy logic controller for each of the four batteries used in the simulation. This chart shows the respective response of each battery during charging to meet at a point.

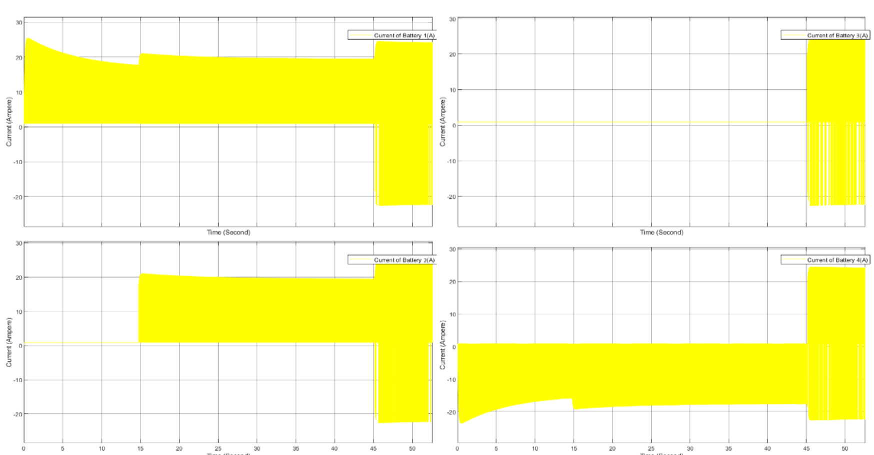

Figure 15: Discharging current with FLC

v. Charging voltage with Fuzzy logic Control

Chart shows the charging voltage with Fuzzy logic controller for each of the four batteries used in the simulation. This chart shows the respective response of each battery during charging to meet at a point.

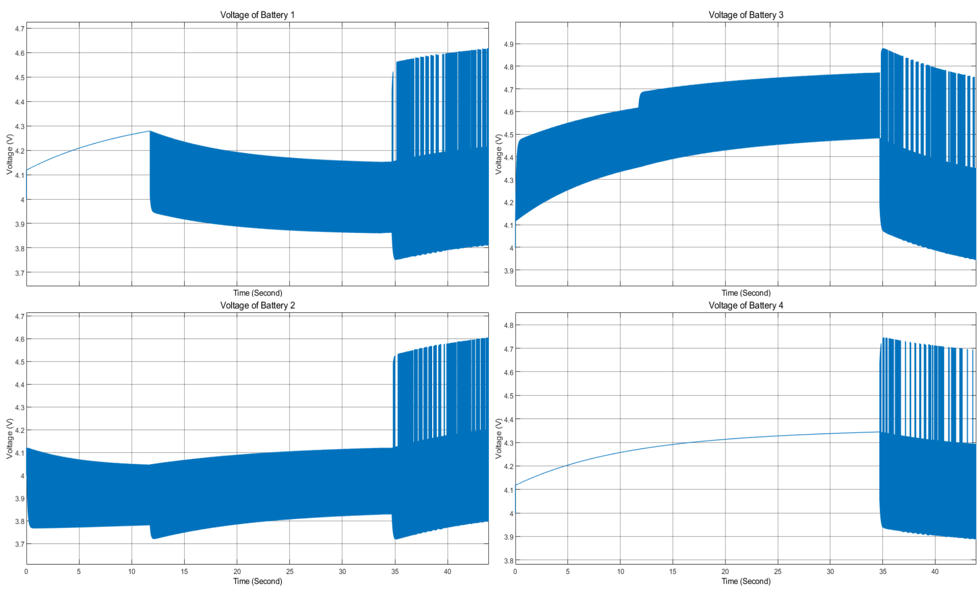

Figure 16: Charging voltage with FLC

vi. Voltage discharging with Fuzzy logic control

Chart shows the discharging voltage with Fuzzy logic controller for each of the four batteries used in the simulation. This chart shows the respective response of each battery during charging to meet at a point.

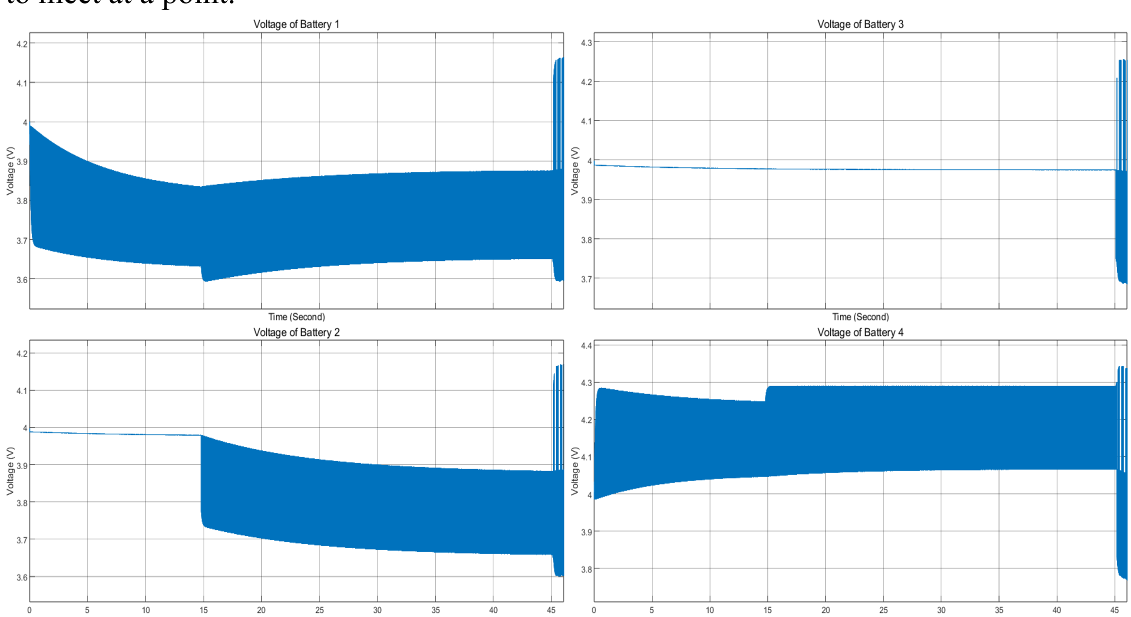

Figure 17: Discharging voltage with FLC

Constant Current (CC) and Constant Voltage (CV) Charging

The constant current (CC) and constant voltage (CV) charging methods work together to ensure efficient and safe battery charging. In the CC phase, the battery is charged at a fixed current, allowing for a rapid increase in charge up to around 80% state of charge (SOC). Once the SOC exceeds 80%, the charging transitions to the CV phase, where a constant voltage is applied, and the current gradually decreases as the battery approaches full charge. This transition prevents overcharging, minimizes heat generation, and extends the battery's lifespan by reducing stress on the cells during the final charging stage.

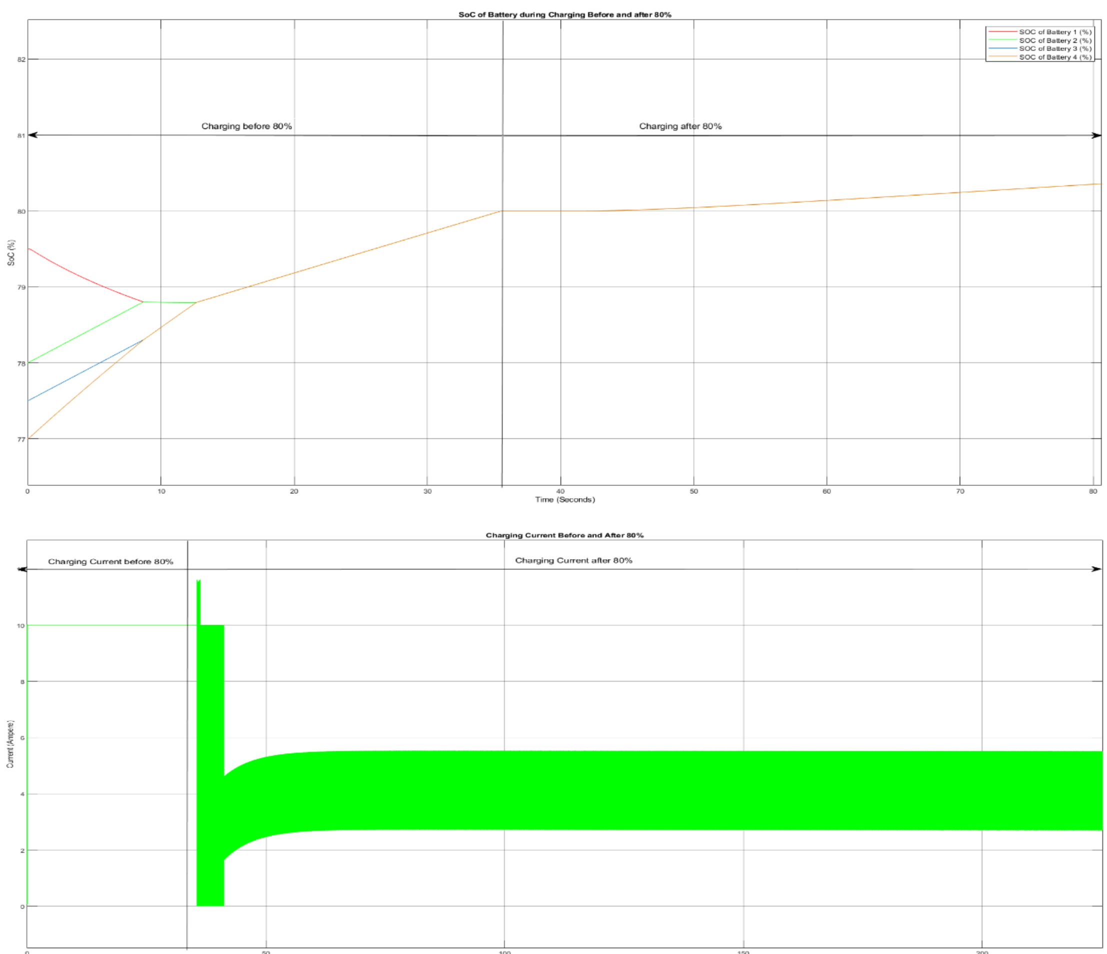

Figure 18:Charging SOC and Current before and after 80%

DISCUSSION

The implementation of a Fuzzy Logic Controller (FLC) improves the overall efficiency of the battery management system. Even though, the charging time is slightly higher with FLC, it ensures better energy distribution among the cells, leading to a higher final state of charge (SOC). This suggests that FLC optimizes the charging process by preventing overcharging of individual cells and ensuring balanced energy transfer. Additionally, the discharging time remains nearly unchanged, implying that FLC primarily enhances the charging and balancing mechanisms without negatively impacting the discharge process. The higher SOC levels achieved with FLC demonstrate its effectiveness in improving battery performance and longevity. By maintaining a more balanced SOC across cells, the system reduces stress on individual batteries, thereby enhancing overall efficiency and lifespan. Therefore, the use of a Fuzzy Logic Controller proves to be a more effective approach for active cell balancing and energy management compared to a system without FLC.

S. N	With FLC		Without FLC	
	Charging	Discharging	Charging	Discharging
Time(s)	34.7	45.2	33	45.5
SoC (%)	69.21	65.55	68.1	65.4

Table 2: Comparison of parameters with and without FLC

CONCLUSION

The project on designing a Fuzzy Logic Controller (FLC) for inductor-based cell balancing in Battery Management Systems (BMS) has successfully addressed key challenges and achieved significant advancements in energy storage technology. By leveraging fuzzy logic principles, the developed FLC optimizes the balancing of individual cells within a battery pack, ensuring efficient energy distribution and prolonged battery life. Inductor-based balancing techniques employed in the system have demonstrated reduced energy losses compared to traditional methods, thereby enhancing overall energy efficiency and minimizing heat generation during operation. Validation through simulations has confirmed the robustness and effectiveness of the FLC in real-world applications. This validation process has underscored the FLC's capability to enhance safety, reliability, and efficiency in diverse battery pack configurations, crucial for applications such as electric vehicles and renewable energy systems. In conclusion, the project represents a significant step forward in advancing battery management technology through innovative FLC design and inductor-based active cell balancing techniques. By addressing current limitations and exploring future opportunities, this work contributes to the ongoing evolution of efficient, reliable, and sustainable energy storage solutions, with implications spanning across automotive, renewable energy, and industrial sectors.

RECOMMENDATION

However, the project has also highlighted several considerations for future development. Addressing the complexity and computational demands of real-time FLC operations, optimizing heat management strategies, and overcoming integration challenges with existing BMS infrastructure are key areas for further refinement. Additionally, ongoing research into advanced control strategies and scalability will be essential to meet evolving industry standards and market demands.

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