Active Cell Balancing for Battery Energy Storage Applications using Fuzzy and ANFIS

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May - 2023

B. Tech

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Certificate

This is to certify that the Project titled "Active Cell Balancing for Battery Energy Storage Applications using Fuzzy and ANFIS" is a bonafide work carried out in the Department of Electrical and Electronics Engineering by Mr. Navadeep Ganesh U bearing Reg. No. 19ETEE003023, Mr. Puneeth V bearing Reg. No. 19ETEE003028, Mr. Rohit C Vasanad bearing Reg. No. 19ETEE003036, Mr. Sudeep K C bearing Reg. No. 19ETEE003041 in partial fulfilment of requirements for the award of B. Tech. Degree in Electrical and Electronics Engineering of M.S. Ramaiah University of Applied Sciences.

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Declaration

Active Cell Balancing for Battery Energy Storage Applications using Fuzzy and ANFIS

The project work is submitted in partial fulfilment of academic requirements for the award of B. Tech. Degree in the Department of Electrical and Electronics Engineering by the Faculty of Engineering and Technology of M. S. Ramaiah University of Applied Sciences. The project report submitted here with is a result of our own work and in conformance to the guidelines on plagiarism as laid out in the University Student Handbook. All sections of the text and results which have been obtained from other sources are fully referenced. We understand that cheating and plagiarism constitute a breach of university regulations, hence this project report has been passed through plagiarism check and the report has been submitted to the supervisor.

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Summary

Active cell balancing is a critical technique used in battery energy storage systems (BESS) to mitigate the performance degradation caused by cell voltage imbalance. This imbalance is commonly observed in multi-cell battery packs, where some cells tend to charge or discharge at a faster rate than others, leading to reduced overall capacity and lifespan of the battery system. To address this issue, researchers have explored the application of fuzzy logic and adaptive neuro-fuzzy inference system (ANFIS) methods to implement active cell balancing algorithms.

Fuzzy logic is a mathematical approach that deals with uncertainty and imprecision by using linguistic variables and if-then rules. ANFIS, on the other hand, combines fuzzy logic and neural network techniques to create a hybrid system capable of learning and adapting to complex input-output relationships. Both methods have shown promise in the field of battery management systems, particularly in the context of cell balancing.

The active cell balancing algorithms based on fuzzy logic or ANFIS typically involve monitoring the voltage levels of individual battery cells and controlling the flow of currents between cells to equalize their voltages. The algorithms employ rules and membership functions to determine the optimal current flow for each cell, ensuring that the voltage across the cells remains within an acceptable range.

The advantage of using fuzzy logic and ANFIS methods lies in their ability to handle the nonlinear behaviour of battery cells and adapt to changing conditions. These algorithms can account for variations in cell characteristics, temperature effects, and aging, enabling efficient balancing even under dynamic operating conditions.

In summary, active cell balancing using fuzzy logic and ANFIS methods offers an effective approach to mitigate voltage imbalance in battery energy storage systems. These algorithms can adapt to varying conditions and optimize the flow of currents between cells, resulting in improved performance and longevity of the battery pack. Further research and development in this area are expected to enhance the effectiveness and applicability of active cell balancing techniques for various battery energy storage applications.

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Nomenclature

Symbol	Abbreviation	Units
aSOC	Average SOC	%
aV	Average Voltage	V
C	Capacitance	Farads
dSOC	Delta SOC	%
dV	Delta Voltage	V
I	Current	A
L	Inductance	H
R	Resistance	Ohm
T	Temperature	ºC
t	Time	s
thSOC	Threshold SOC	%
V	Voltage	V

Abbreviation and Acronyms

ANFIS	Adaptive Neuro Fuzzy Inference System
BESS	Battery Energy Storage System
BMS	Battery Management System
CC-CV	Constant Current-Constant Voltage
EOL	End of Life
FIS	Fuzzy Inference System
FL	Fuzzy logic
Li-Ion	Lithium Ion
NMC	Nickel Manganese Cobalt
OCV	Open Circuit Voltage
PWM	Pulse Width Modulation
RMSE	Root Mean Squared Error
SOC	State of Charge
SOH	State of Health
UPS	Uninterrupted Power Supply

1. Introduction

Nowadays, considering the sharp rise in energy demand and mounting government pressure to comply with environmental regulations, moving forward and increasing the use of clean energy became necessary. But this energy fluctuates and is influenced by its environment. The direction of creating energy storage systems has changed over the years. Batteries play a crucial role in the development of portable electronic devices, electric vehicles, and biomedical devices. The ability to produce electrochemical storage and transformation is demonstrated by this requirement. There are numerous battery types with various features and qualities. Due to their advantages, particularly their high volumetric and gravimetric energy and power densities, high voltages, long lifespans, and lack of pronounced memory effects, lithium-ion (Li-ion) batteries are the preferred option in ESS. To meet the high voltage requirements of these applications, Li-ion cells must be coupled in series and parallel combinations.

The behaviour of Li-Ion batteries, which are a non-linear system with variable characteristics over time due to charging and discharging processes, must be monitored and controlled to achieve the best performance while safeguarding the batteries from overcharging, over-discharging, overheating, and a balancing act on connecting cells in series during the charging process. Specific voltage, current, and temperature restrictions should be upheld to safeguard the battery and prevent fires and explosions. This process is known as the battery management system (BMS).

Because it allows for the monitoring of the battery's characteristics, BMS is seen as essential when employing lithium-ion batteries. Voltage, current, temperature, state of charge (SoC), state of health (SoH), and end of life (EOL) are some of the properties. To maintain an acceptable battery status and life, it also regulates the battery charging procedure The goal of BMS is to balance the batteries while they are being charged and perform monitoring of the battery parameters.

There are two types of balancing processes, they are:

1. Passive balancing
2. Active balancing

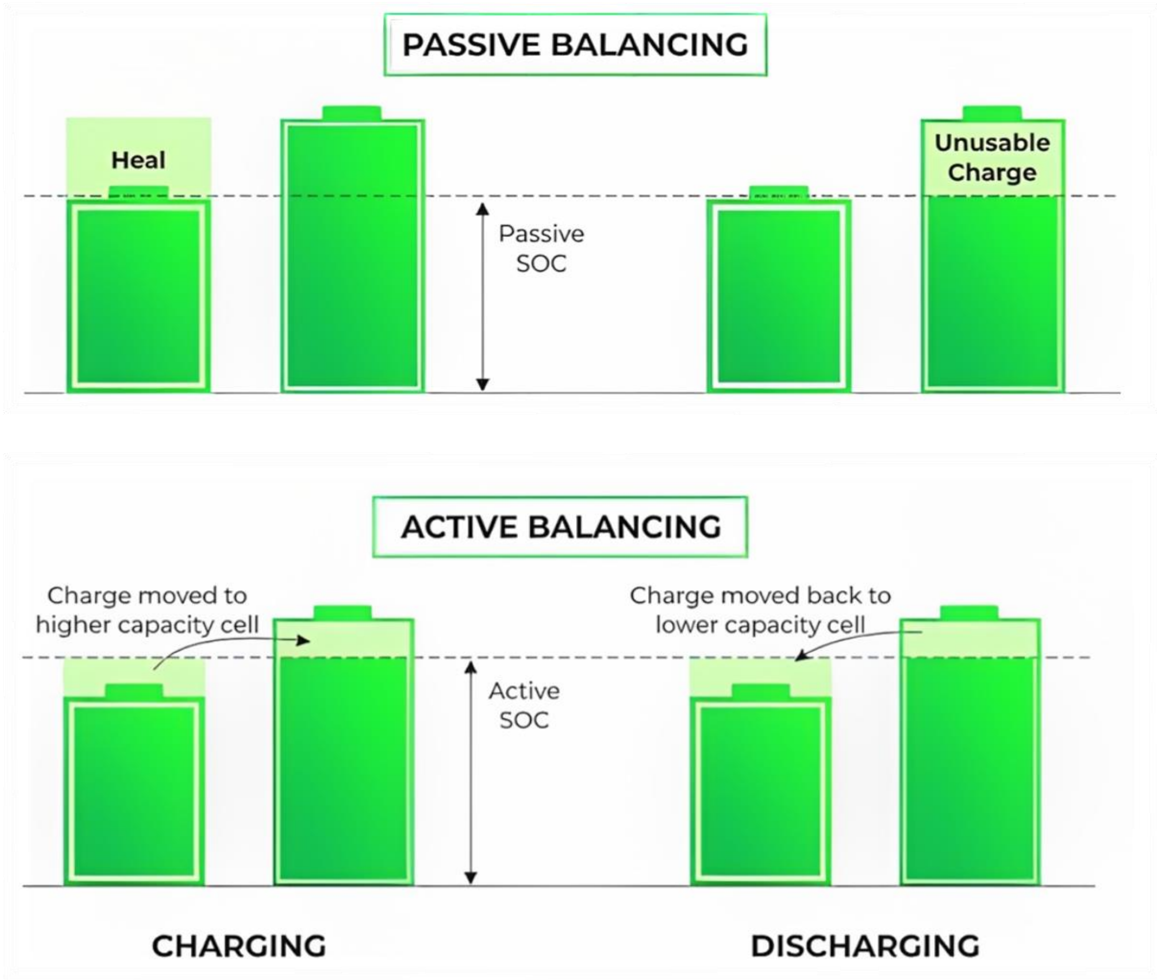

Figure 1: Comparison of active and passive balancing

The passive balancing is the widely used variety in all the mere applications. BMS is widely used in small power applications, including uninterrupted power supplies (UPS) and inverter systems, smart grids, electric vehicles, and solar energy.

In the voltage based FIS method, the balancing process wasn't completed in the bounded time of 200s. Cell characteristics is a factor that effects this behaviour as the OCV/SOC curve is not in linear relationship with voltage and only at higher and lower SOC points, these tend to be linear as it is highlighted in cell chemistry the figure above. So the voltage based direct SOC relation isn't promisingly accurate and this method may be suitable for a low compute application where a complex algorithm like a fuzzy system cannot be run.

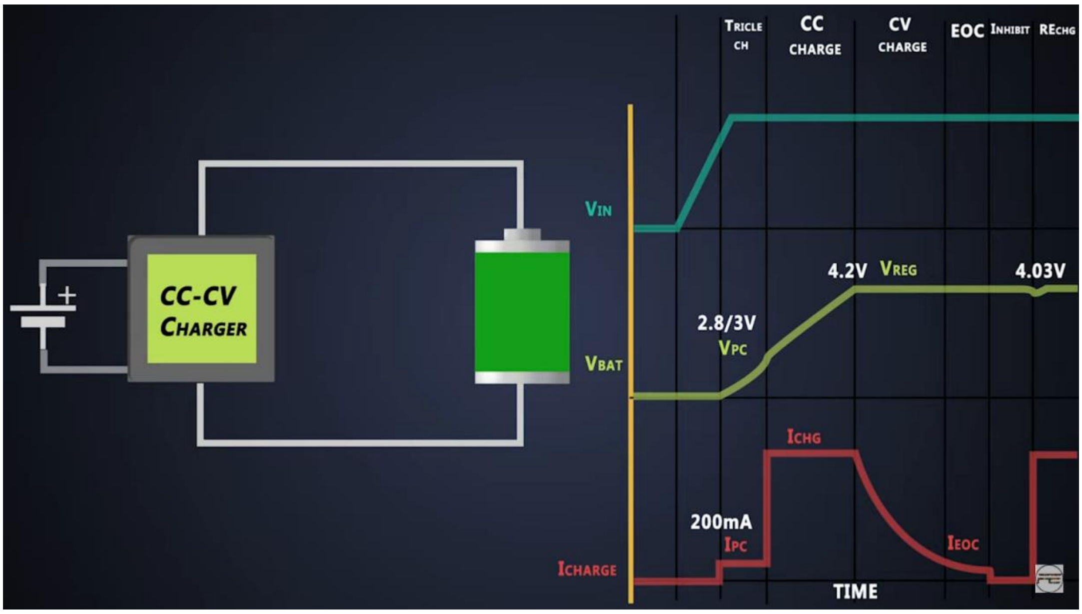

Figure 2: CC-CV charging in Li-Ion battery

In this project 'Active Cell Balancing using Fuzzy Methods for Battery Energy Storage System', we aim at utilising a single inductor-based charge bank for momentarily storing the charge from the cell with state of charge (SoC) imbalance and transferring it to the cell with a lower SoC so as to maintain the cells in a battery pack at uniform SoC to optimise run-time and charging. This involves having a control loop that decides which cell to balance and from where by continuously monitoring the individual cell SoC. The algorithm to carry out this balancing decision and the control loop parameter are implemented using the fuzzy logic technique. Overall, the system includes monitoring, decision making and control blocks.

As shown in Figure 3, this cell balancing method uses single inductor (L). This cell balancing circuit's control algorithm chooses a cell to transfer energy to after detecting each cell's voltage or SOC. Uneven cell energy is transmitted to an inductor when MOSFETs (Qn) are turned on and off. In this circuit, a higher-energy cell in the battery string transfers uneven cell energy to a lower-energy cell through an inductor. Figure 3 illustrates a cell-balancing circuit with a single inductor that is both compact and inexpensive.

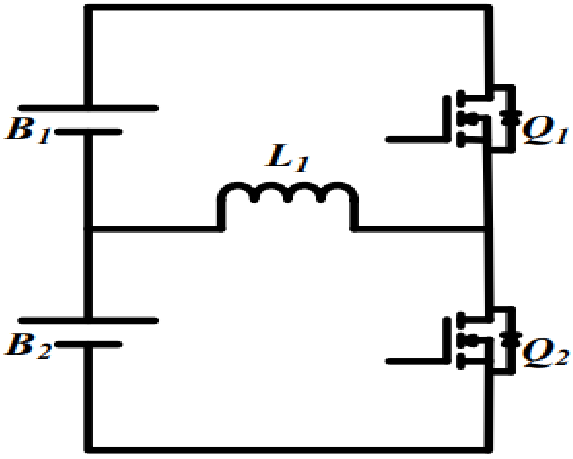

Figure 3: Single balancing stage circuit

In this project, models for the following three methods are developed, tested and the comparison is made between them regarding the speed, advantages and disadvantages.

Method 1 - Fuzzy logic-based method with fuzzy inference system (FIS) using Voltage

Method 2 - Fuzzy logic-based method with fuzzy inference system (FIS) using SOC

Method 3 - Fuzzy logic-based method with adaptive neural fuzzy inference system (ANFIS)

2. Background Theory

2.1 Cell Balancing Topologies:

To reach the needed capacity or voltage, the BESS cells are linked as strings in parallel or series whichever it is depending on. However, a BESS frequently experiences state-of-charge (SoC) cell imbalance, which can be brought on by endogenous or external causes and events. Internal impedance, charge storage volume, self-discharge rate, and manufacturing process variance are examples of endogenous causes. Exogenous factors include the uneven temperature distribution within a BESS, which affects how quickly individual cells age and discharge energy. Moreover, charging and discharging the cells in an unequal number of cycles leads to SoC imbalance among them.

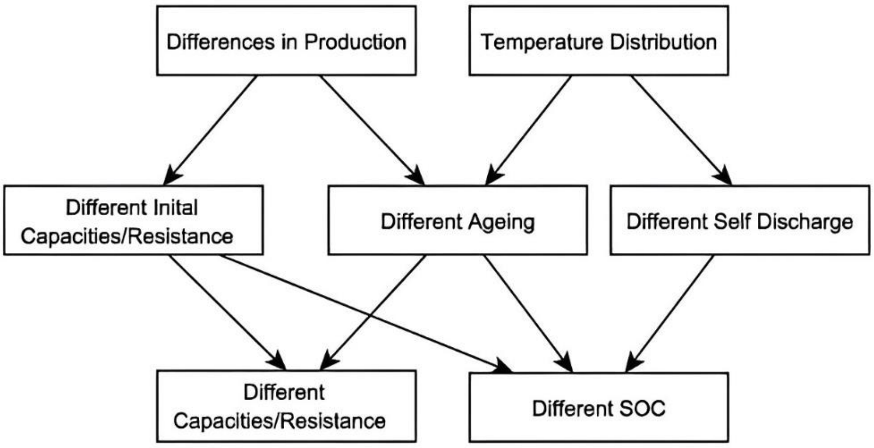

Figure 4: Map of causes for imbalance in the cells

In recent decades, a lot of cell balancing topologies have been proposed, which are categorised into two main groups as active and passive topologies based on their energy storage elements utilized and energy balancing ways among the cells illustrated in Figure 5.

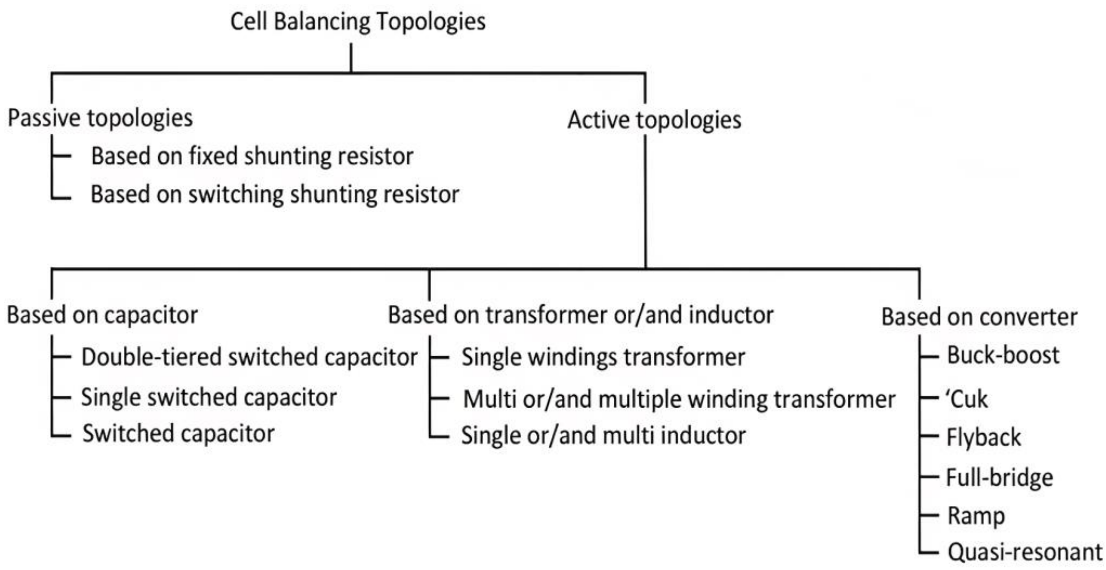

Figure 5: Map of different cell balancing topologies

The primary distinction between active and passive cell balancing is shown in Figure 5 by the impact on cells' SoC of their use. For the sake of clarification, let's assume that a battery pack contains three cells, designated cell A, cell B, and cell C, with respective SoC levels of 85%, 75%, and 65% prior to balancing. To achieve the passive cell balancing goal of all cells having the same level of SoC as the lowest cell, cell C (65%), energy from the cells with greater SoC was dissipated. As a result, the system's efficiency will decline. In contrast to passive cell balancing, active cell balancing has been proposed by researchers to achieve high system efficiency and SoC balancing speed in a short period of time. The fundamental idea is to distribute energy equally among the cells by moving energy from cells with a higher SoC (such as cell A) to cells with a lower SoC (such as cell C). As a result, the cells' SOC will be equal, or 75% in this case.

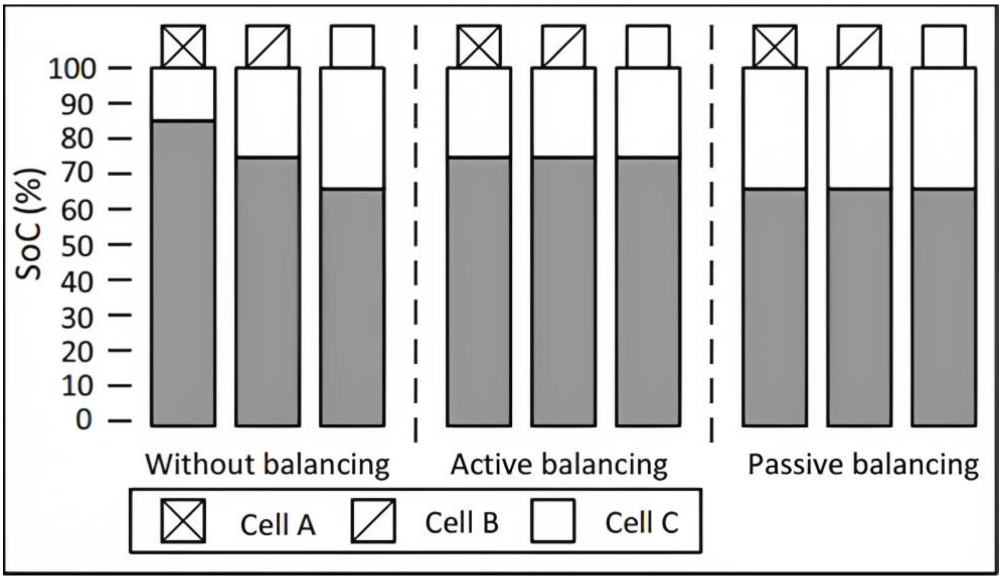

Figure 6: Comparison of active and passive cell balancing on cells SoC

2.2 Literature Review:

A high-efficiency bidirectional active balance for electric vehicle battery packs based on model predictive control. This paper (Song, et al., 2018)develops a model predictive control (MPC)-based active equilibrium control technique for series battery packs. Bidirectional active equalization is modelled and analysed, and the model predictive control method is then applied to the created state space equation to reduce equalization time and wasteful energy usage. In each cycle, the optimization problem that reduces the equilibrium time is converted to a linear programming form. Online linear programming is used to find a set of optimal control solutions and decouple the series equalization problem. By dynamically altering the equalization current, the equalization time is decreased. The MPC method can prevent wasteful energy transfer and save equalization time, according to simulation results. The bench experimental result shows that the equilibrium time is reduced by 31%, verifying the rationality of the MPC strategy.

A Review of Passive and Active Battery Balancing based on MATLAB/Simulink (Daowd, et al., 2011). The cells' unbalance is a significant issue affecting battery systems. Without a balancing device, the voltages of the individual cells will fluctuate over time, rapidly reducing the capacity of the battery pack. This will cause the entire battery system to fail. Thus, cell balance is crucial for prolonging battery life. For battery packs, various cell-balancing approaches have been suggested. In this study, various proposed balancing topologies for battery strings based on MATLAB/Simulink simulation are reviewed and compared. Circuit design, balancing simulation, voltage/current stress, real-world implementations, application, balancing speed, complexity, balancing system efficiency, size, cost, and other factors have all been taken into consideration.

Equalization of lithium-ion battery pack based on fuzzy logic control in electric vehicle (Ma, 2018.) Fuzzy logic control (FLC)-based non-dissipative equalization is proposed to reduce the inconsistency of series-connected lithium-ion batteries. The equalization circuit prepares the way for hardware module-based equalization and is designed to accomplish the equalization of cell to cell for battery packs. It is a two-stage bidirectional equalization circuit with energy-transferring inductors. The Venin equivalent circuit model of a lithium-ion battery and the Extended Kalman Filter (EKF) method are both used in this paper's proposal for equalization based on state of charge (SOC). The FLC is recommended to cut down on energy usage and equalization time for efficient equalization. The FLC strategy is built using a collection of membership functions to explain the equalization behaviour of the cells.

To demonstrate the benefits of the suggested scheme, the proposed FLC is compared to the mean-difference algorithm. According to simulation results, FLC outperforms the mean-difference algorithm in terms of equalization time and standard deviation of final SOC under NEDC operating conditions by 23% and 18.5%, respectively. 5.54% more energy is saved when using the mean-difference approach. Additionally, the two-stage bidirectional equalization circuit enhances consistency and performs well.

Overview of cell balancing methods for Li-ion battery technology (Hemavathi, 2020.) Numerous factors, including overvoltage, undervoltage, overcharge and discharge current, thermal runaway, and cell voltage imbalance, have an impact on lithium-ion batteries. Cell imbalance, which over time changes the voltage of each cell in the battery pack and subsequently rapidly reduces battery capacity, is one of the most important issues. The battery cells should be regularly equalized to keep the differential between the cells as small as possible to prolong the lifespan of the battery pack. For the battery pack, a variety of cell-balancing strategies have been presented. Based on cell voltage and state of charge (SOC), it is divided into passive and active cell balancing techniques. By dissipating energy from higher-SOC cells, the passive cell balancing technique equalizes the state of charge of the cells and makes all cells with similar SOCs equal to the lowest-level cell SOC. The SOC of the cells will be equal because of the active cell balancing process, which transfers energy from higher SOC cells to lower SOC cells. This review article provides a summary of various proposed cell balancing techniques for Li-ion batteries that can be used for energy storage and automotive applications.

In this paper, (Ahmad, et al., 2019.) A review on Cell balancing topologies in battery energy storage systems. Cell imbalance has a significant impact on a battery energy storage system's performance. Cell imbalance's primary drawback is the capacity degradation of each individual cell, which results in underutilization of a BESS's available capacity. Common causes of cell imbalance include manufacturing errors, variations in the self-discharge rate, and discharging the cells over an uneven number of cycles. Accordingly, over the past ten years, researchers have put forth several cell-balancing topologies. The proposed cell balancing topologies for BESSs are reviewed in this research. Four criteria are compared: application types, balancing speed, charge/discharge capability, and key components needed to balance an n-cell.

A fast multi-switched inductor balancing system based on a fuzzy logic controller for lithium-ion battery packs in electric vehicles (Cui, et al., 2017.) Instead of using the current proportional-integral (PI) controller, a fuzzy logic (FL) controller is suggested to improve the balancing performance of lithium-ion battery packs. This is based on a low-cost multi-switched inductor balancing circuit (MSIBC). The open circuit voltages (OCVs) of a cell and their variations throughout the pack are used as inputs in the proposed FL controller, and the FL controller's output is the balancing current. The FL controller for the MSIBC has an advantage over the current PI controller in that it can maintain high balancing currents during nearly the entire balancing process for various lithium battery types. As a result, more pack capacity can be recovered because the suggested FL controller completes battery pack balancing in a lot less time. This will help to improve the pack performance in electric vehicles and extend the serving time of the battery pack.

Comparison on cell balancing methods for energy storage applications (Lee, et al., 2016.). Batteries may lose capacity and have negative effects on their safety and lifespan due to unbalanced cells that result from variations in cell compositions and initial charge capacities. Methods: For use in energy storage systems, this article compares various cell balancing techniques. According to how resistors are used, this study initially classifies cell balancing circuits as either passive or active cell balancing techniques. The benefits and drawbacks of both passive and active cell balancing techniques are then examined in this research. A fixed shunting resistor circuit and a switching shunting resistor circuit are two of the passive cells balancing techniques under investigation. In addition, cell balancers using capacitors, inductors, transformers, or DC-DC converters are among the active cell balancing techniques examined in this research.

In the paper (Manickavasagam, et al., 2013.) Neuro-fuzzy-based control for parallel cascade control. The use of adaptive neuro-fuzzy inference system (ANFIS) control for a parallel cascade control system is covered in this paper. Two controllers, the primary and secondary controllers in a parallel cascade, are used. The primary controller in this paper is created using a neuro-fuzzy technique. The basic goal of a fuzzy controller is to govern poorly defined and challenging-to-model plants by mimicking human thinking. However, there is no established process for creating fuzzy controllers. The neural network offers strong learning, optimization, and adaptive capabilities. Fuzzy logic tuning issues and design challenges may be resolved using a combination of neural networks and fuzzy logic. These two models are combined to create more reliable learning systems known as the adaptive neuro-fuzzy inference system (ANFIS) because of their complementary advantages. The internal model control approach is used to construct the secondary controller. Different case studies are used to evaluate the performance of the proposed ANFIS-based control, and the simulation results show that it performs better in terms of servo and regulatory control than the traditional proportional integral derivative controller.

3. Aim and Objectives

3.1 Title

Fuzzy logic based active cell balancing method for battery energy storage system applications.

3.2 Aim

To study and develop an active cell balancing algorithm for battery system application and compare the usage of different fuzzy inference system by model-based design.

3.3 Objectives

1. Conduct a comprehensive literature review to gain an understanding of existing methodologies for cell balancing using fuzzy logic. This step involves studying previous research and publications related to fuzzy logic-based cell balancing techniques.
2. Simulate the basic building blocks for active cell balancing and study the principles and concepts of fuzzy logic. This involves developing simulation models to understand the behaviour of active cell balancing systems and how fuzzy logic can be applied to control and optimize the balancing process.
3. Develop an active balancing algorithm using a basic fuzzy inference system. This step includes designing and implementing a fuzzy logic-based algorithm for cell balancing. The algorithm should take into account input parameters such as State of Charge (SoC), voltage, and other relevant factors. The developed algorithm will be validated through simulation to assess its effectiveness in achieving cell balancing.
4. Design simulation models that consider various input parameters and utilize different fuzzy logic-based systems. This step involves creating simulation models that incorporate different input variables, membership functions, rules, and fuzzy logic systems. By varying these parameters, the behaviour and performance of the cell balancing process can be analysed and evaluated.

5. Compare the outputs obtained from different methods of active cell balancing. This involves analysing and comparing the results obtained from different fuzzy logic-based approaches and methodologies. The evaluation should consider factors such as balancing speed, accuracy, efficiency, and overall suitability for practical applications. Based on the comparison, conclusions can be drawn regarding the effectiveness and applicability of these methods for real-world cell balancing scenarios.

By accomplishing these objectives, the project aims to contribute to the understanding and advancement of fuzzy logic-based cell balancing techniques and provide insights into their potential applications in various industries.

3.4 Methods and Approach to attain each objective

Objective No.	Statement of the Objective	Methodology	Resources Utilised
1	To perform a literature review and learning about methodologies of cell balancing using fuzzy logic.	• Conducted a comprehensive literature survey from conference papers, journals and chip manufacturer application notes and manuals to learn about the problem, study the methods and implementations. • Understood the gaps in the literature, commonly used methods and how it can be implemented and tested in multiple other ways for greater accuracy and optimization.	Research papers and application notes

2	To simulate the basic building block for active balancing and studying about fuzzy logic.	• Designing a basic inductor based switching logic using MOSFETS and duty cycle control to test active balancing. • Calculation of component values and specifications for the use case using mathematical equations based on the inductor current and voltage values.	Research papers and application notes
3	To develop an active balancing algorithm applying basic fuzzy inference system and their validation in simulation.	• Applied fuzzy logic based MOSFET duty cycle control signal for driving the stages of balancing. • Created a set of fuzzy logic rules and membership functions with Mamdani based fuzzy inference system taking SOC input from the cell stack.	Books, MATLAB 2021a documentation and SIMULINK block sets

4	To design simulation models considering different input parameters and using different fuzzy based systems.	• Designed another model using adaptive neuro fuzzy inference system, performed the training process and tested the output. • In the previous model that based on the cell SOC input values, used the cell voltage and tested the output.	Research papers and MATLAB 2021a documentation
5	To compare the output from different methods of active cell balancing and drawing a conclusion about suitability of these for applications.	• Comparison of fuzzy inference and adaptive neuro fuzzy systems, relation between them and analyzed the results to decide the improvement in speed and computation required to run the model.	Research papers and related online blogs, statistics

4. Problem Solving

4.1 Design and Development

In this project 'Active Cell Balancing using Fuzzy Logic for Battery Energy Systems using Fuzzy and ANFIS', we aim at utilising an inductor-based balancing method to store the charge momentarily from the cell with a state of charge and transferring it to the cell with a lower SoC to maintain the cells in a battery pack at uniform SoC to optimise run-time power utilization and charging. This involves having a control loop that decides which cell to balance and from which pair in a series string by continuously monitoring the individual cell SoCs. The algorithm to carry out this balancing decision and the control loop parameter are implemented using the fuzzy logic technique. Overall, the system includes monitoring, decision making and control blocks which is further described in the next section.

4.1.1 System level Block Diagram

Method 1:

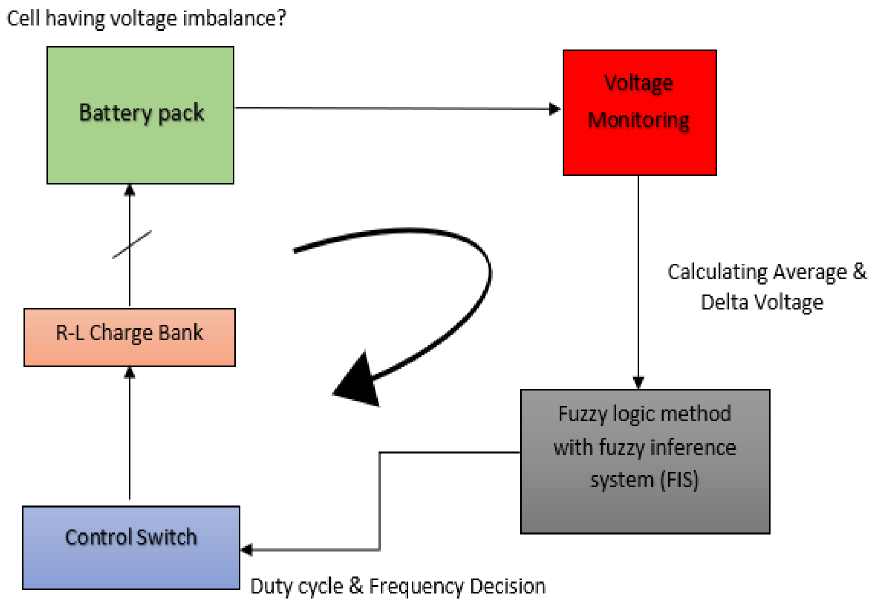

Figure 7: System level block diagram for voltage based method using FIS

Method 2:

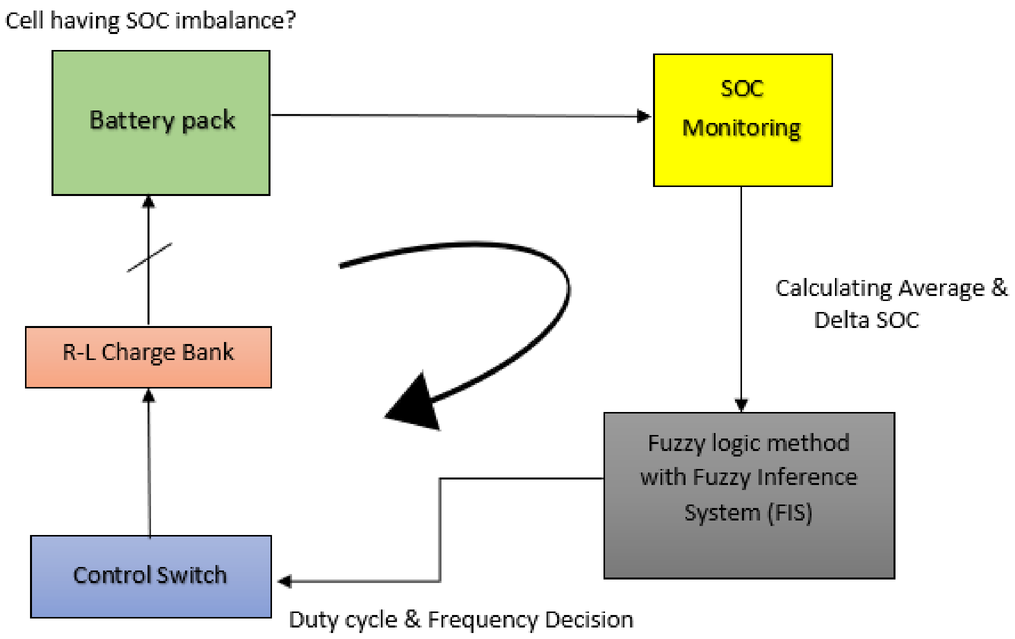

Figure 8: System level block diagram for SOC based method using FIS

Method 3:

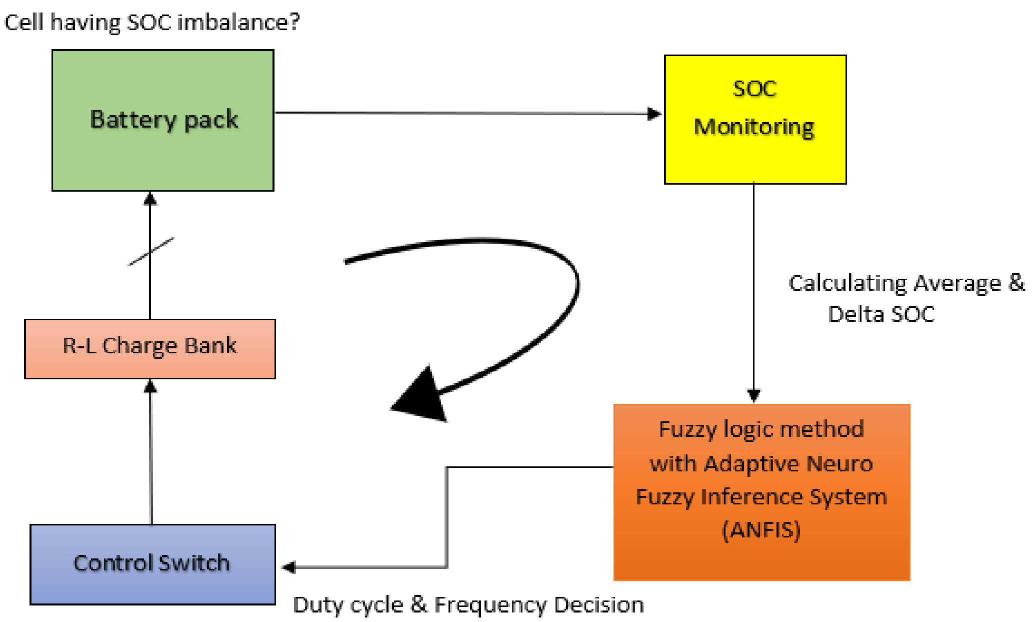

Figure 9: System level block diagram for SOC based method using ANFIS

4.1.2 Active Cell Balancing Circuit Design

This is the main functional unit in the system and the working of the individual block is explained here. The same is expanded here on for a multi-cell battery pack. In this circuit, two cells are considered connected in series with their voltage and SoC monitored. This is possible in the MATLAB battery model to directly probe the battery parameters. Linked in common is an inductor that acts as a charge bank to momentarily store the charge based on the action of the N-MOSFETs connecting in loop with it

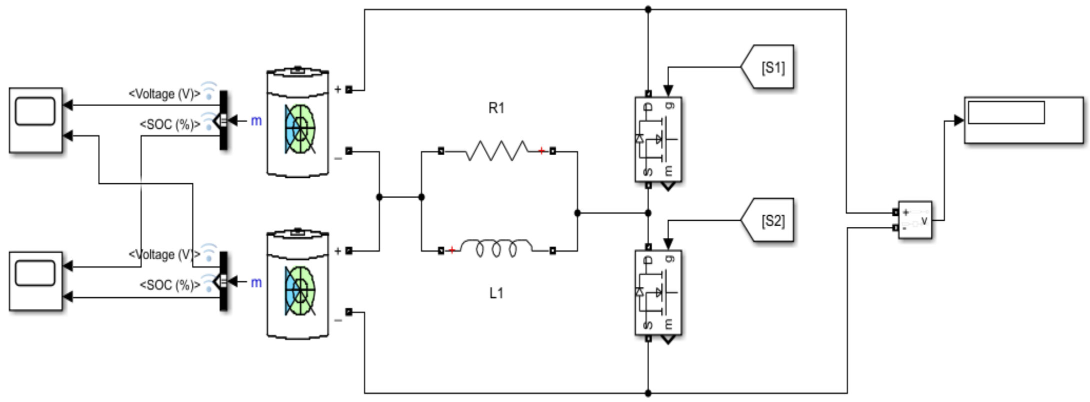

Figure 10: Active cell balancing circuit block

The cell balancing process can be visualized as individual loops for each cell pair. Let's consider an example with cell 1 and cell 2. If cell 1 has a higher State of Charge (SoC) than cell 2, MOSFET1 turns ON, allowing current to flow in a clockwise direction through the inductor L1. This current charges the inductor temporarily. As a result, the voltage across the inductor becomes greater than the voltage of cell 2.

Due to this voltage difference, the current flows in an anticlockwise direction through the body diode of MOSFET2. This current is directed towards cell 2, effectively charging it. It is important to note that in this context, SoC and voltage are used interchangeably, although they may not be directly proportional to each other. Additionally, there is a resistor R1 connected in parallel with inductor L1. This resistor serves the purpose of degaussing the inductor when it is fully charged or saturated. It helps to dissipate any excess energy stored in the inductor, ensuring efficient operation of the balancing system. By employing this loop structure for each cell pair, the system can actively balance the individual cell SoC values by transferring charge between cells, ensuring that all cells reach a balanced state.

Say, $V_{cell1} > V_{cell2}$

where V_{cell1} and V_{cell2} are individual cell voltages.

MOSFET turn ON time, $t_{on} = D \times \frac{1}{f_g}$ (1)

where D is the duty cycle at which the MOSFET is driven and f_g is the frequency of the gate signal.

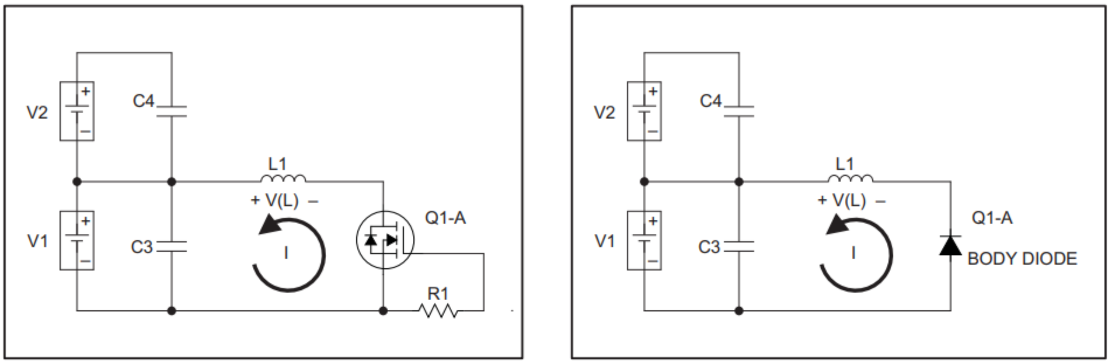

Figure 11: Individual stages of cell balancing

The inductor current and voltage across it is given by,

$$i_L(t = t_{ON}) = \frac{V2}{r_{DS(on)}}\left(1 - e^{-t_{ON}\frac{r_{DS(on)}}{L}}\right) = I_{PEAK} \quad (2)$$

where $V2$ is the cell 2 voltage, $r_{DS(on)}$ is the MOSFET drain to source ON state resistance, t_{ON} is the MOSFET ON time.

$$V_L(t) = L\,\frac{dI_L}{dt} = L\,\frac{\Delta I_L}{t_{OFF} - t_{ON}} = V1 + V_F \qquad (3)$$

where ΔI_L is the change in inductor current, V_F is the diode forward voltage.

In the voltage based FIS method, the balancing process wasn't completed in the bounded time of 200s. Cell characteristics is a factor that effects this behaviour as the OCV/SOC curve is not in linear relationship with voltage and only at higher and lower SOC points, these tend to be linear as it is highlighted in cell chemistry the figure above. So the voltage based direct SOC relation isn't promisingly accurate and this method may be suitable for a low compute application where a complex algorithm like a fuzzy system cannot be run.

Item	Specification
3.1 Nominal discharge capacity	2,500mAh Charge: 1.25A, 4.20V,CCCV 125mA cut-off, Discharge: 0.2C, 2.5V discharge cut-off
3.2 Nominal voltage	3.6V
3.3 Standard charge	CCCV, 1.25A, 4.20 ± 0.05 V, 125mA cut-off
3.4 Rapid charge	CCCV, 4A, 4.20 ± 0.05 V, 100mA cut-off
3.6 Charging time	Standard charge : 180min / 125mA cut-off Rapid charge: 60min (at 25℃) / 100mA cut-off
3.7 Max. continuous discharge (Continuous)	20A(at 25℃), 60% at 250 cycle
3.8 Discharge cut-off voltage End of discharge	2.5V
3.9 Cell weight	45.0g max
3.10 Cell dimension	Height : 64.85 ± 0.15mm Diameter : 18.33 ± 0.07mm
3.11 Operating temperature (surface temperature)	Charge : 0 to 50℃ (recommended recharge release < 45℃) Discharge: -20 to 75℃ (recommended re-discharge release < 60℃)
3.12 Storage temperature (Recovery 90% after storage)	1.5 year -30~25℃(1*) 3 months -30~45℃(1*) 1 month -30~60℃(1*)

Table 1: INR18650 cell datasheet specifications

4.1.4 R-L bank inductor choice

The decision for inductor value is made from the balancing current estimate relating to the above-mentioned equation. An inductor of 56uH is chosen here and since the storage of charge in the inductor is momentary, a reasonably high value of current is required to charge the accepting battery. 10A peak rated inductor current is chosen for this purpose and a 2K Ohm resistor is chosen for degaussing of this low value inductor. This building block is scaled across series of cells one each for a cell pair.

4.2 Simulation and Implementation

4.2.1 System Flowchart

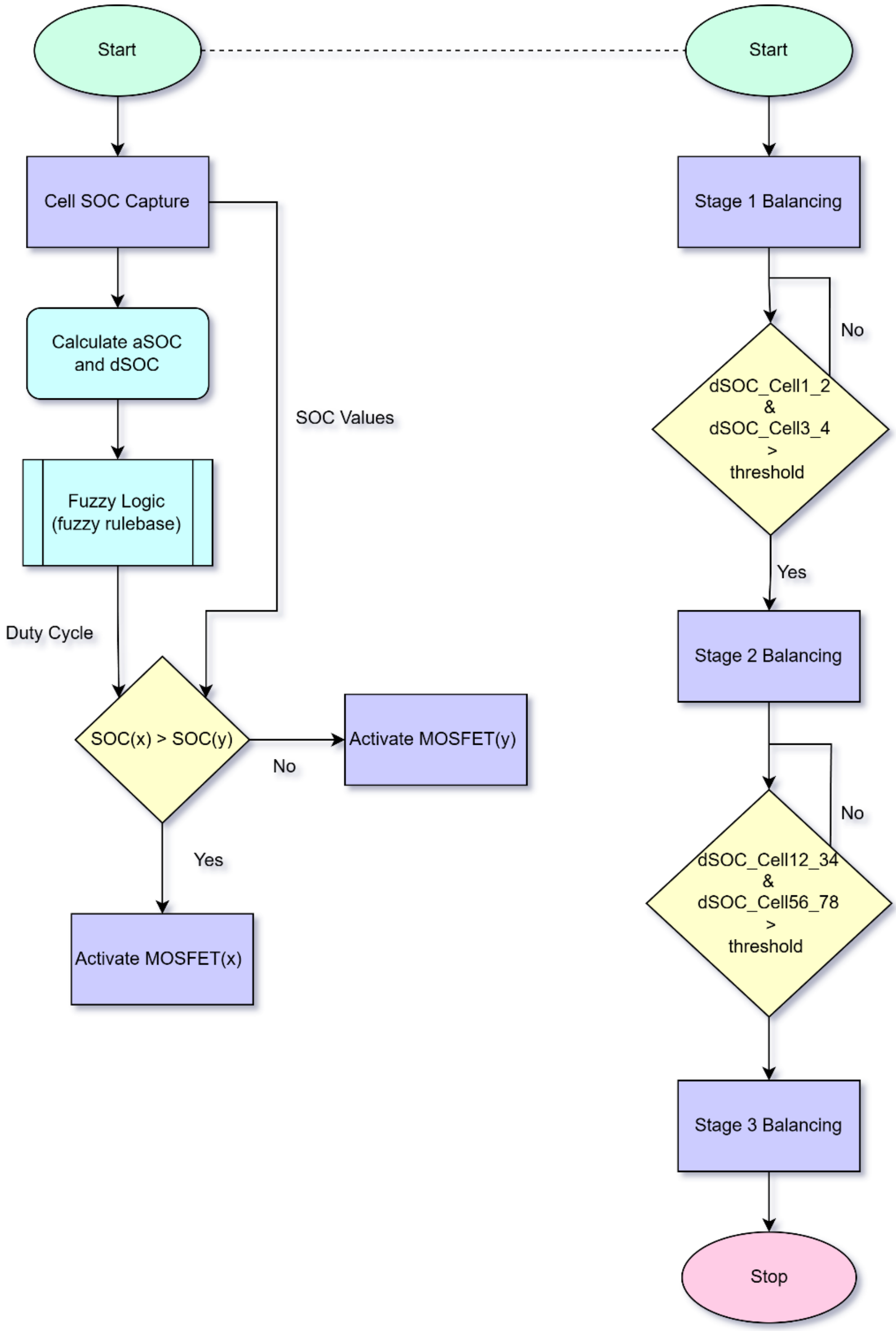

Figure 12: Functional system flowchart

4.2.2 Average and Delta Voltage Blocks

Method 1:

With the individual cell voltage being monitored, the fuzzy logic is used to make a decision of duty cycle output to control the MOSFETs. To parameterize it based on the cell data, average voltage(aV) and delta voltage(dV) are calculated prior to providing the input to the fuzzy block. So essentially, these two are the crisp inputs to fuzzy blocks carrying details about the cell parameters.

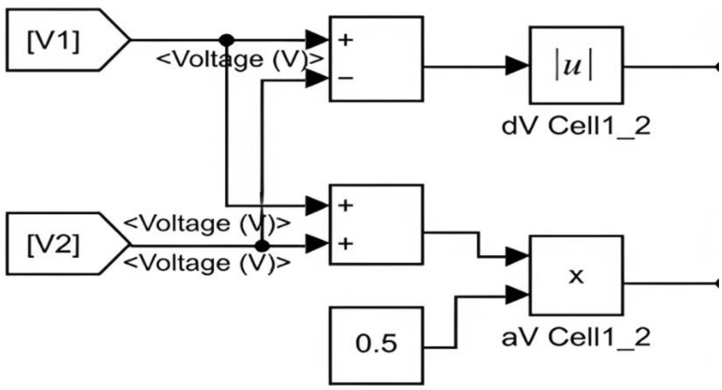

Figure 13: Voltage input calculation block

Further, certain fuzzy rules are framed based on these inputs and mapped accordingly to the output side. It can be noted that all the variables in the fuzzy rules are relative to the pair of cells. For example, dV Cell1_2 is the difference between the voltage of cell 1 and cell 2.

Method 2 and 3:

With the individual cell SoC being monitored, the fuzzy logic is used to make a decision of duty cycle output to control the MOSFETs. To parameterize it based on the cell data, average SoC(aSoC) and delta SoC(dSoC) is calculated prior to providing the input to the fuzzy block. So essentially, these two are the crisp inputs to fuzzy blocks carrying details about the cell parameters.

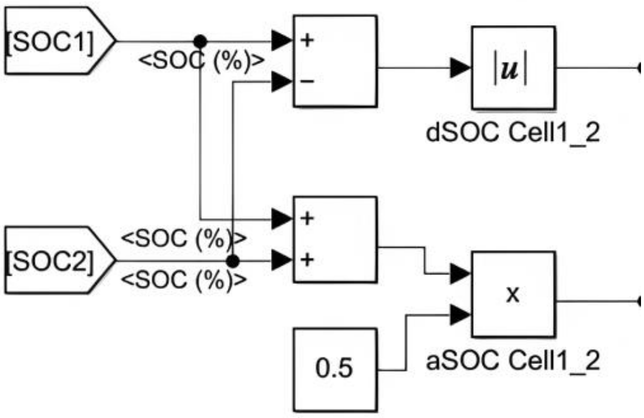

Figure 14: SOC input calculation block

Further, certain fuzzy rules are framed based on these inputs and mapped accordingly to the output side. It can be noted that all the variables in the fuzzy rules are relative to pair of cells (example: dSoC1_2 is the different between SoC of cell1 and cell2)

1. If (dSOC1_2 is LOW) and (aSOC1_2 is HIGH) then (Out1_2 is LOW) (1)
2. If (dSOC1_2 is LOW) and (aSOC1_2 is MID) then (Out1_2 is MIDLOW) (1)
3. If (dSOC1_2 is LOW) and (aSOC1_2 is LOW) then (Out1_2 is MID) (1)
4. If (dSOC1_2 is MID) and (aSOC1_2 is HIGH) then (Out1_2 is MID) (1)
5. If (dSOC1_2 is MID) and (aSOC1_2 is MID) then (Out1_2 is MIDHIGH) (1)
6. If (dSOC1_2 is MID) and (aSOC1_2 is LOW) then (Out1_2 is HIGH) (1)
7. If (dSOC1_2 is HIGH) and (aSOC1_2 is LOW) then (Out1_2 is HIGH) (1)
8. If (dSOC1_2 is HIGH) and (aSOC1_2 is MID) then (Out1_2 is HIGH) (1)
9. If (dSOC1_2 is HIGH) and (aSOC1_2 is HIGH) then (Out1_2 is HIGH) (1)
10. If (dSOC1_2 is ZERO) or (aSOC1_2 is ZERO) then (Out1_2 is ZERO) (1)

Figure 15: Fuzzy rules for SOC method

4.2.3 MOSFET Control Signal

The output variable in this system controls the gate of the NMOS (n-channel metal-oxide-semiconductor) to initiate the cell balancing process. This output variable, represented as a duty cycle, dynamically adjusts the balancing current based on the inputs of average State of Charge(aSoC) and delta State of Charge(dSoC). The duty cycle value sweeps across a range to optimally regulate the balancing current.

The state of the cell is carefully monitored, and according to the fuzzy rule, if the average SoC of the cells is low and the deltaSoC(dSoC) between them is high, a high balancing current is allowed. This indicates that there is a significant potential for charging the cell. Conversely, if the average SoC is high, approaching the cell's full charge level, the balancing current is appropriately regulated to avoid overcharging. This behaviour is evident in the figure below, where the duty cycle is reduced as the cells charge. This reduction in duty cycle helps regulate the balancing current and ensures a healthy charge/discharge cycle for the cells. By adjusting the duty cycle, the system optimizes the balancing process based on the specific characteristics of each cell and the desired balancing objectives.

The figure visually illustrates the relationship between the duty cycle and the charging process, showcasing the system's ability to dynamically adapt the balancing current according to the cells' state and requirements.

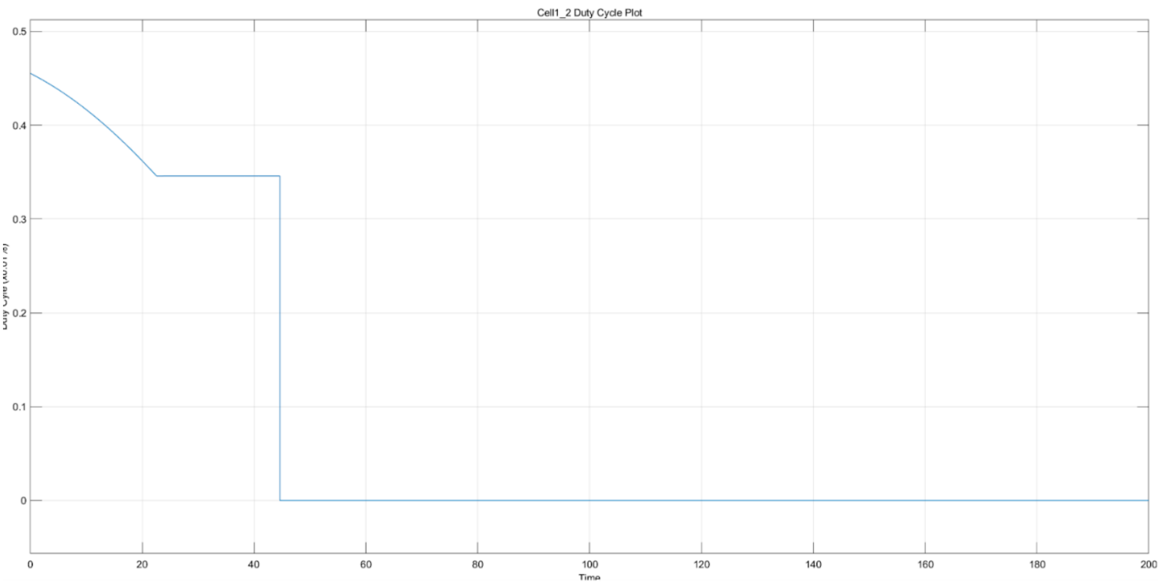

Figure 16: Cell1_2 Duty cycle plot

4.2.4 Fuzzy Logic block (Membership function, Input/Output)

This is the primary functional block of the system and system block design remains same for all three methods except the input which is voltage in this first method. In the Fuzzy Logic Controller block, a file related to the method used existing in the same working directory is referenced.

Method 1:

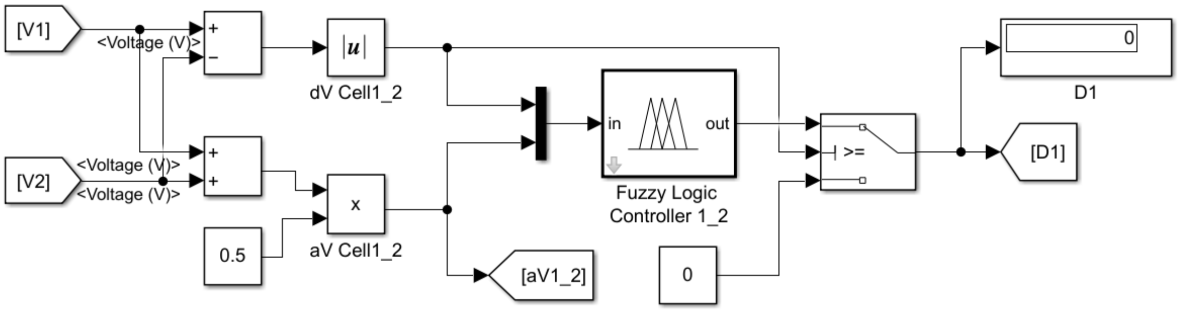

Figure 17: Fuzzy model design for voltage based method

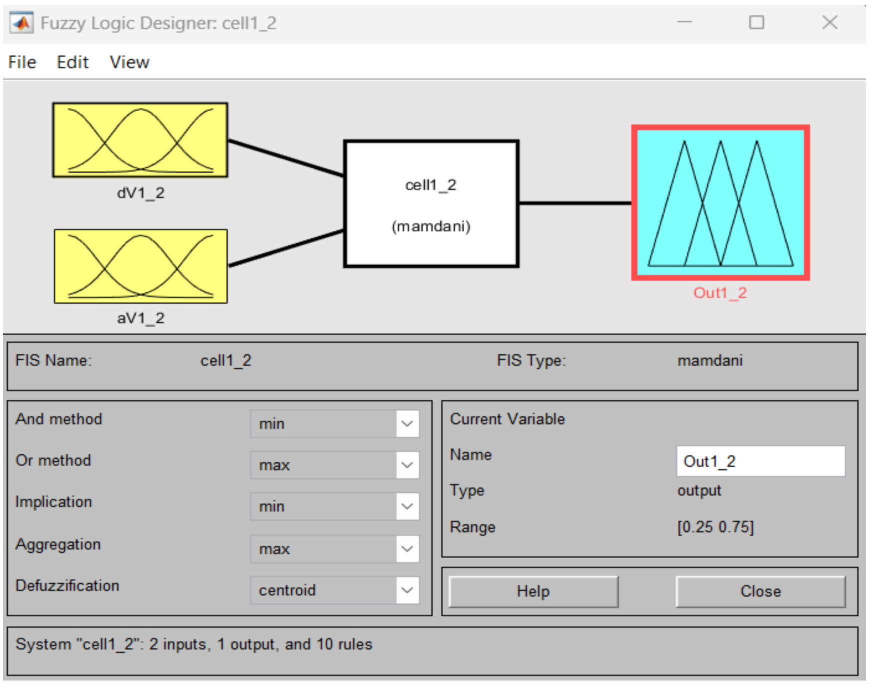

Figure 18: Voltage method setup using fuzzy designer

The Mamdani fuzzy inference system is employed, which consists of two input variables and one output variable. The input variables in this case are related to voltage parameters. The range for each input variable is determined based on the specific input and output requirements of the system. To define the behaviour and decision-making process of the fuzzy inference system, fuzzy rules are established. These rules capture the relationships between the input variables and the corresponding membership function conditions. By considering different combinations of input variables, the fuzzy rules cover all possible mappings from the inputs to the membership function conditions.

In total, 10 fuzzy rules are defined to govern the operation of the system. These rules ensure that the system can handle a wide range of input scenarios and make appropriate decisions based on the given inputs. Each fuzzy rule represents a specific combination of input conditions and their corresponding output actions.

The utilization of the Mamdani fuzzy inference system, along with the defined fuzzy rules, enables the system to effectively process the input voltages and determine the appropriate output action. By considering the linguistic variables and membership functions associated with each input and output variable, the system can perform accurate and intelligent decision-making based on the provided rules and the given input voltages.

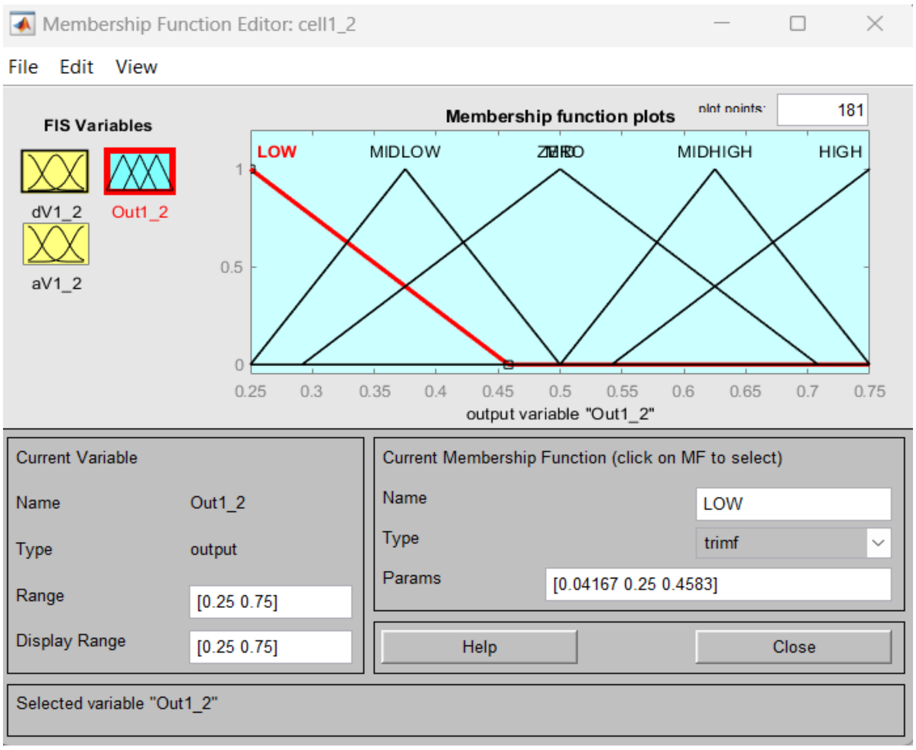

Figure 19: Voltage method membership function setup

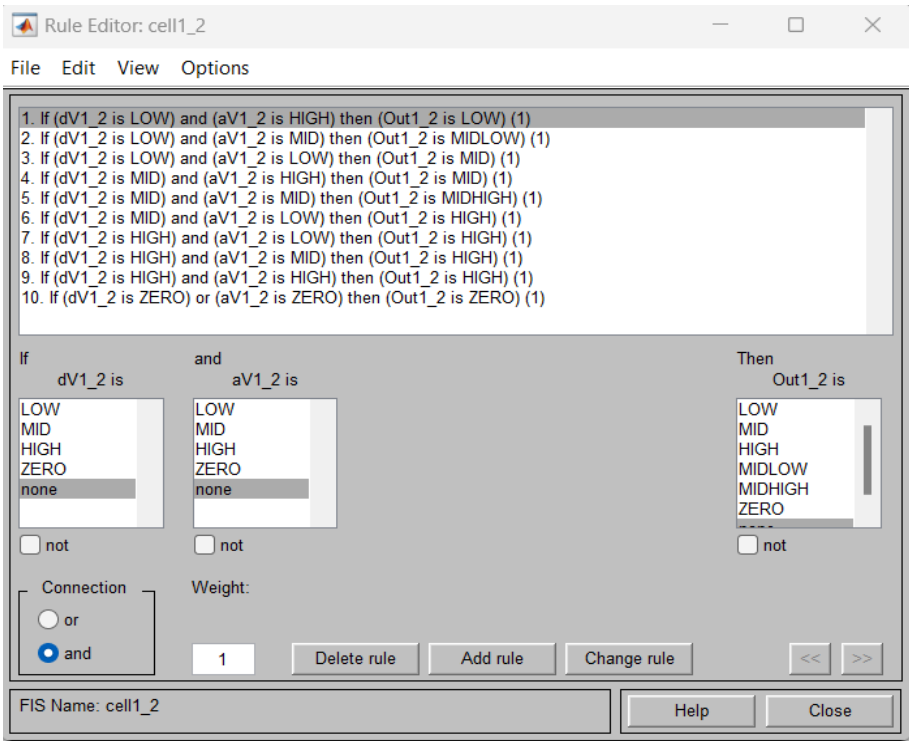

Figure 20: Fuzzy rules for voltage based method

Method 2:

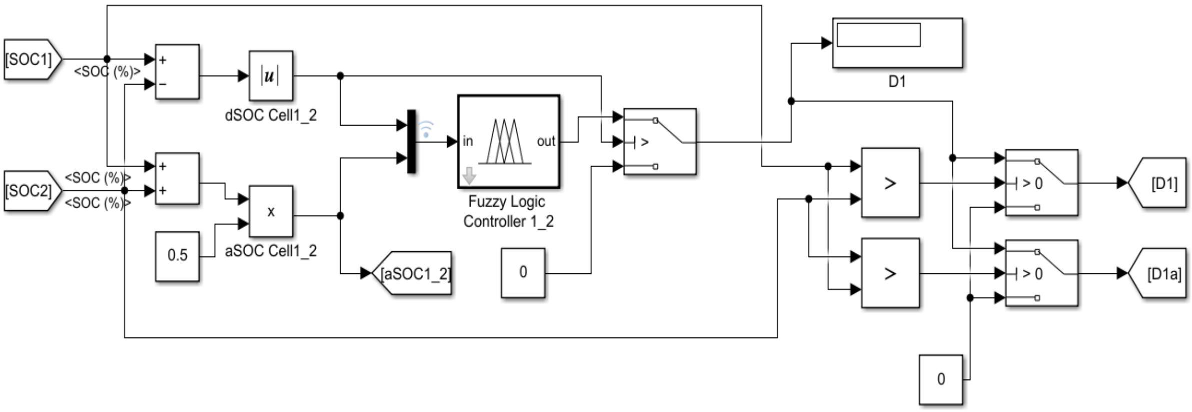

Figure 21: FIS model for SOC based method

The functional block diagram of the SOC-based method is similar to the voltage-based method, as it also utilizes a Mamdani fuzzy inference system. However, there are differences in the membership functions and fuzzy rules used in this system, which are specifically tailored for the SOC input variables. In the SOC-based method, the membership functions for the input variables are defined based on the specific characteristics and range of the SOC values. These membership functions capture the linguistic information associated with the SOC input variables, allowing the fuzzy inference system to interpret and process the inputs effectively.

The fuzzy rules in this system are designed to establish the relationships between the SOC input variables and the desired output actions. These rules dictate how the system should respond based on different combinations of SOC values.

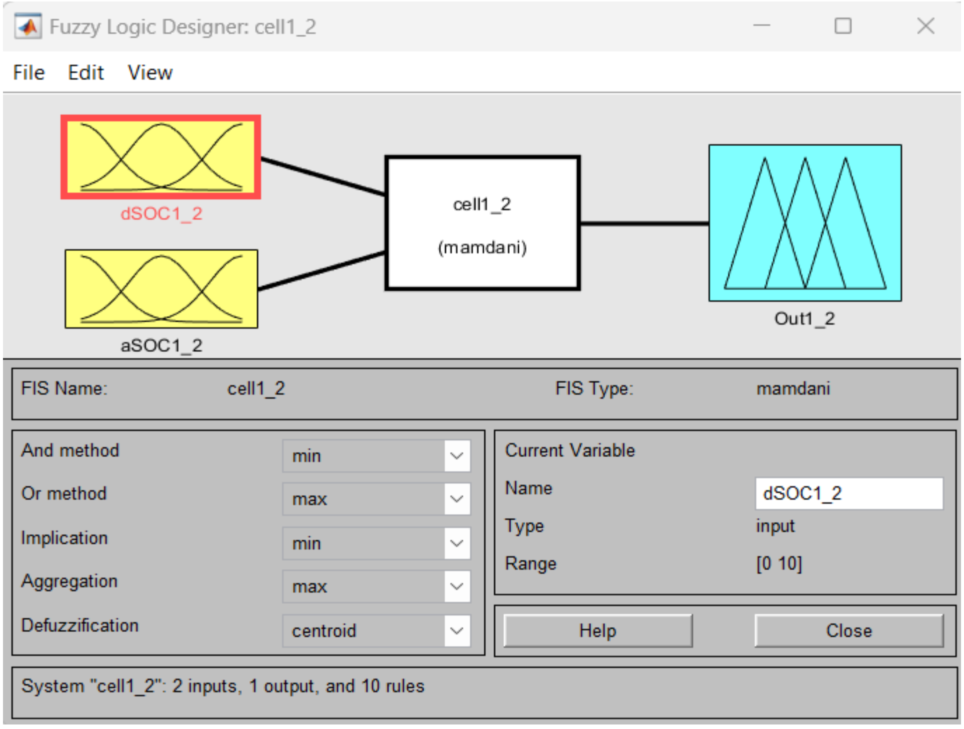

Figure 22: Fuzzy designer setup for SOC based method

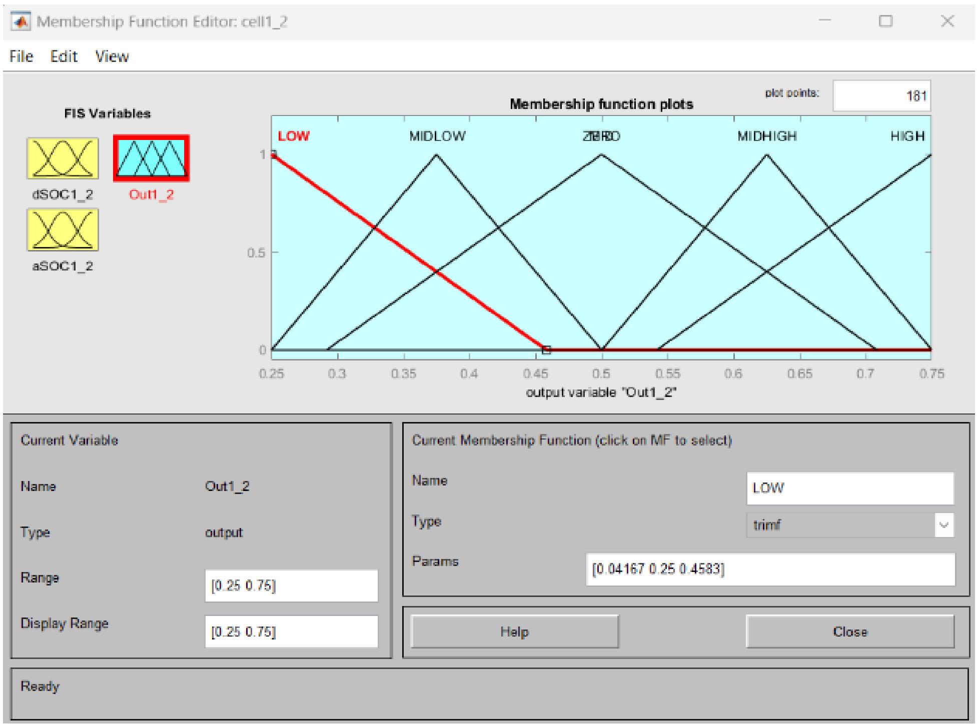

Figure 23: Membership function setup for SOC method

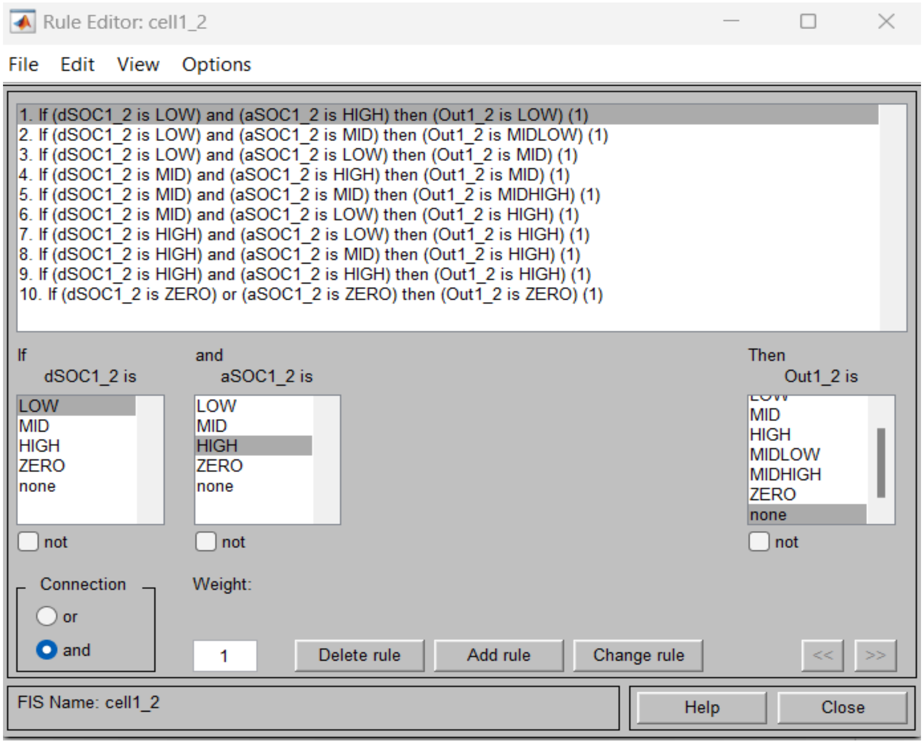

Figure 24: Fuzzy rules for SOC method

Method 3:

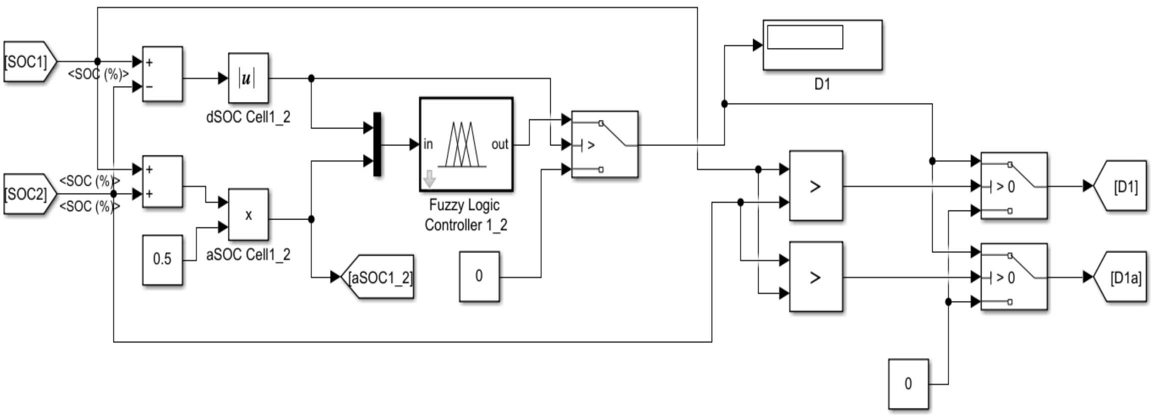

Figure 25: ANFIS model for SOC based method

In this approach, the membership function mappings and fuzzy rules are not explicitly defined by the user. Instead, they are determined by the fuzzy inference system based on training data. The training data is obtained from a simulated system that is similar to the one being studied. Through the training process, the fuzzy inference system learns and adapts to the data, allowing it to map the appropriate duty cycle values using the output membership functions. These membership functions capture the relationship between the input variables and the desired output in a fuzzy manner. After the fuzzy inference process, the output is defuzzied to convert it into a crisp value, providing a clear and actionable result.

By training the fuzzy inference system with appropriate data, it becomes capable of inferring the most suitable duty cycle value based on the inputs and the desired outcome. This adaptive nature of the system allows it to handle complex and non-linear relationships between the variables, leading to effective and optimized cell balancing. The use of training data and the fuzzy inference system ensures that the algorithm can adapt to different operating conditions and improve its performance over time. This data-driven approach enhances the robustness and accuracy of the cell balancing process, providing a more reliable and efficient solution.

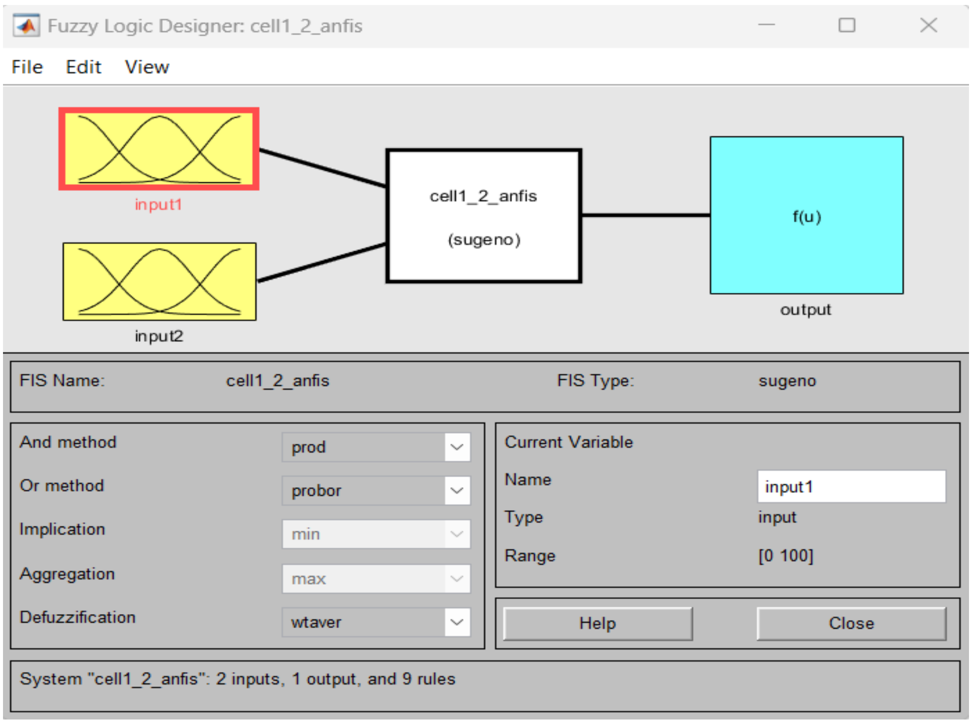

Figure 26: Fuzzy logic designer setup for ANFIS

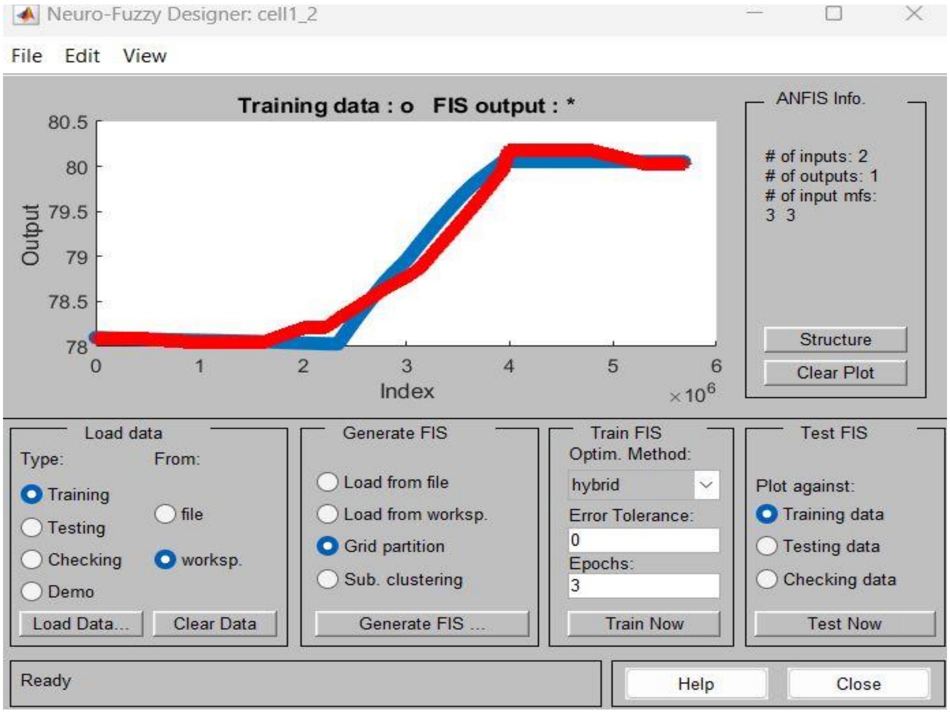

Figure 27: Neuro-Fuzzy training for ANFIS

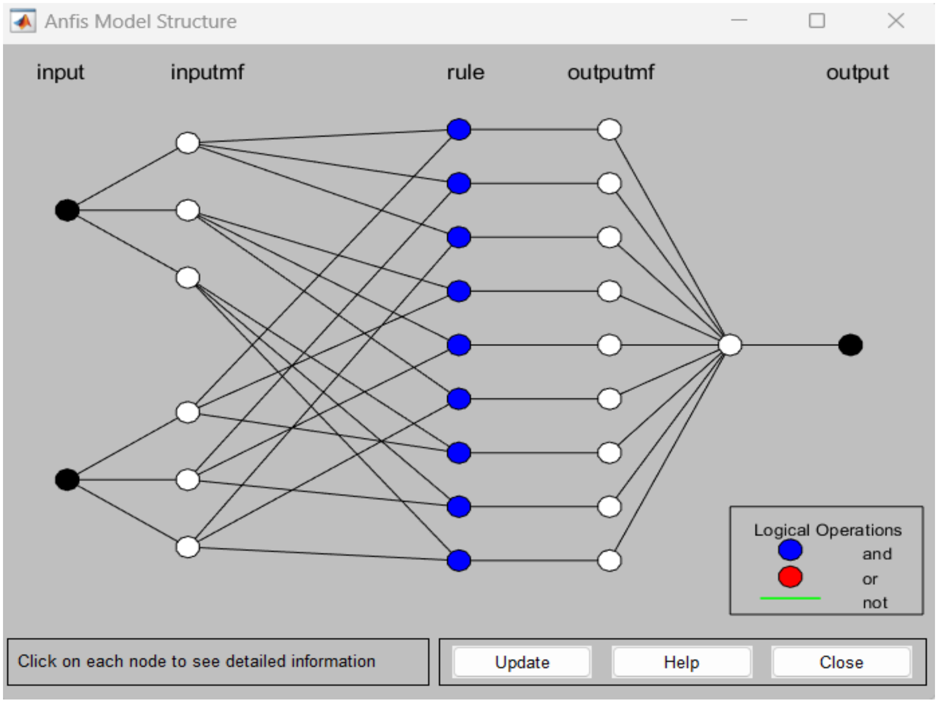

Figure 28: ANFIS model structure mapping

The training data here is loaded from the workspace and the FIS is generated using the default grid partitioning method. Grid partitioning forms a partition by dividing the input space into several fuzzy slices, each of which is specified by a membership function for each feature dimension. In the next step, the training is done specifying the Epochs number. The training status is shown in the command window and once done, the model is ready to be tested against the input training data. The blue plot above shows the training data and the red plot is the FIS output generated. The training RMSE is less than 0.13336.

ANFIS info:

Number of nodes: 35

Number of linear parameters: 9

Number of nonlinear parameters: 24

Total number of parameters: 33

Number of fuzzy rules: 9

5. Result

5.1 Method 1

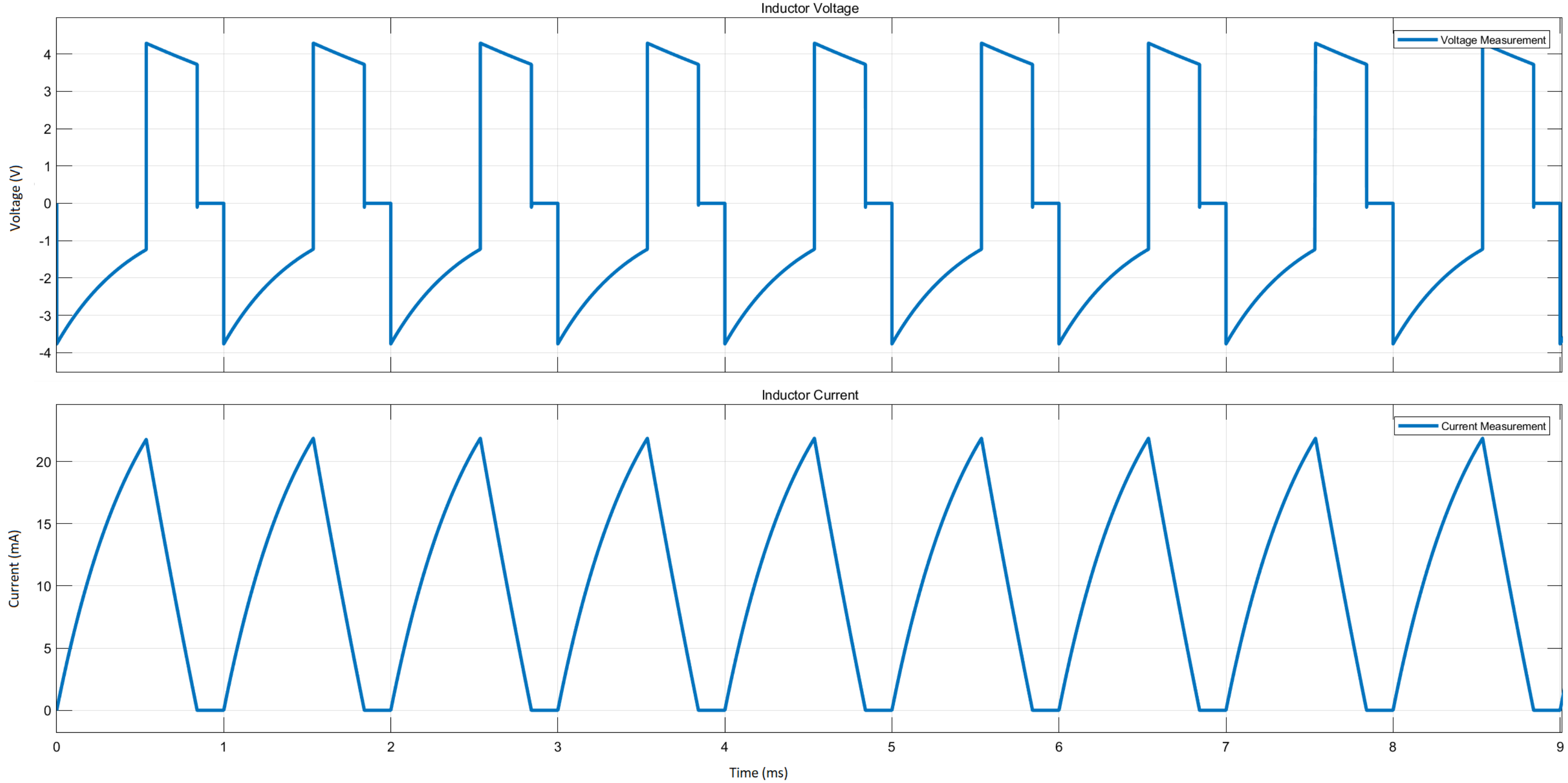

Figure 29: Inductor voltage and current plot for voltage method using FIS

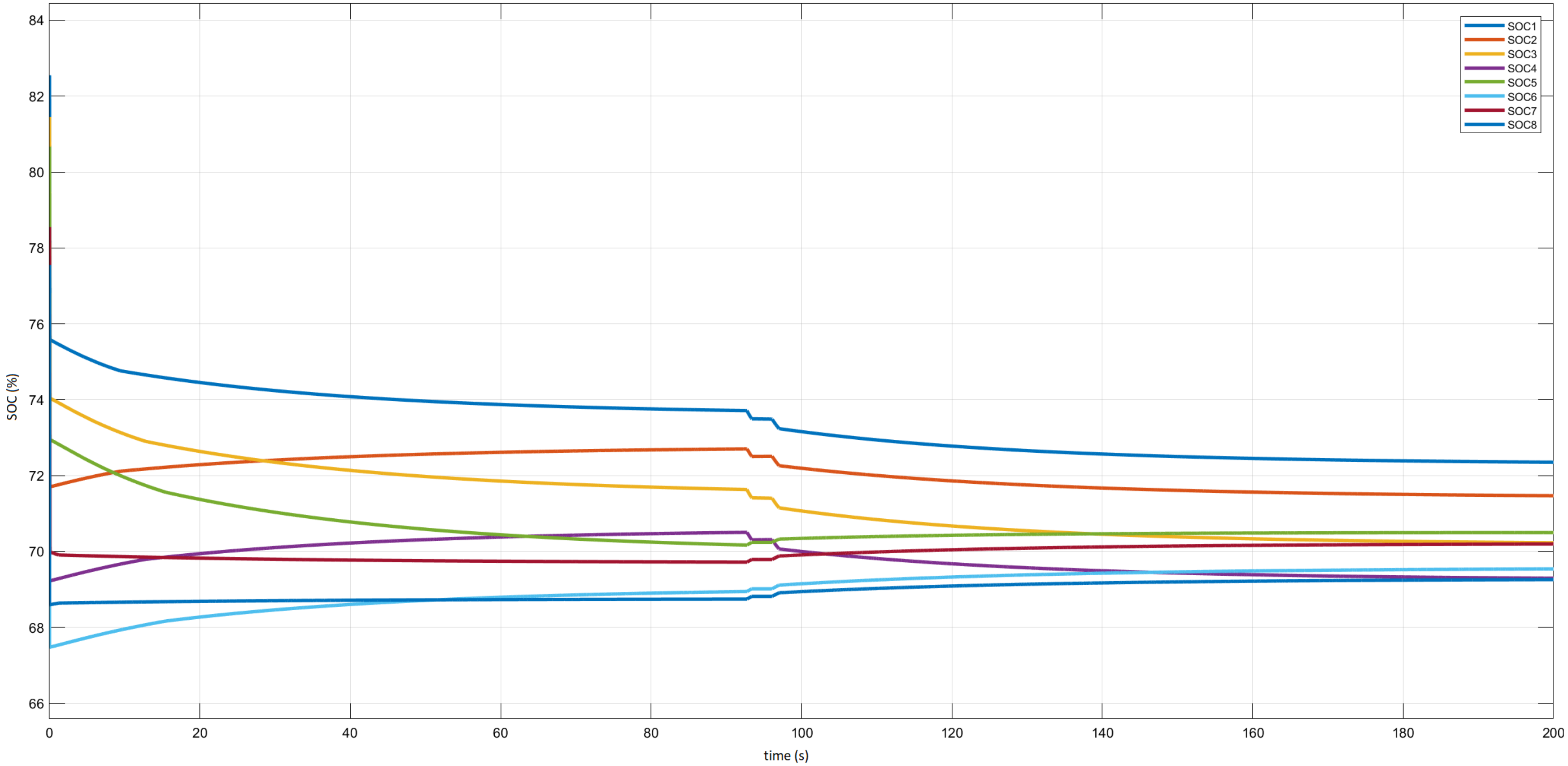

Figure 30: Cell SOC balancing status for voltage method using FIS

5.2 Method 2

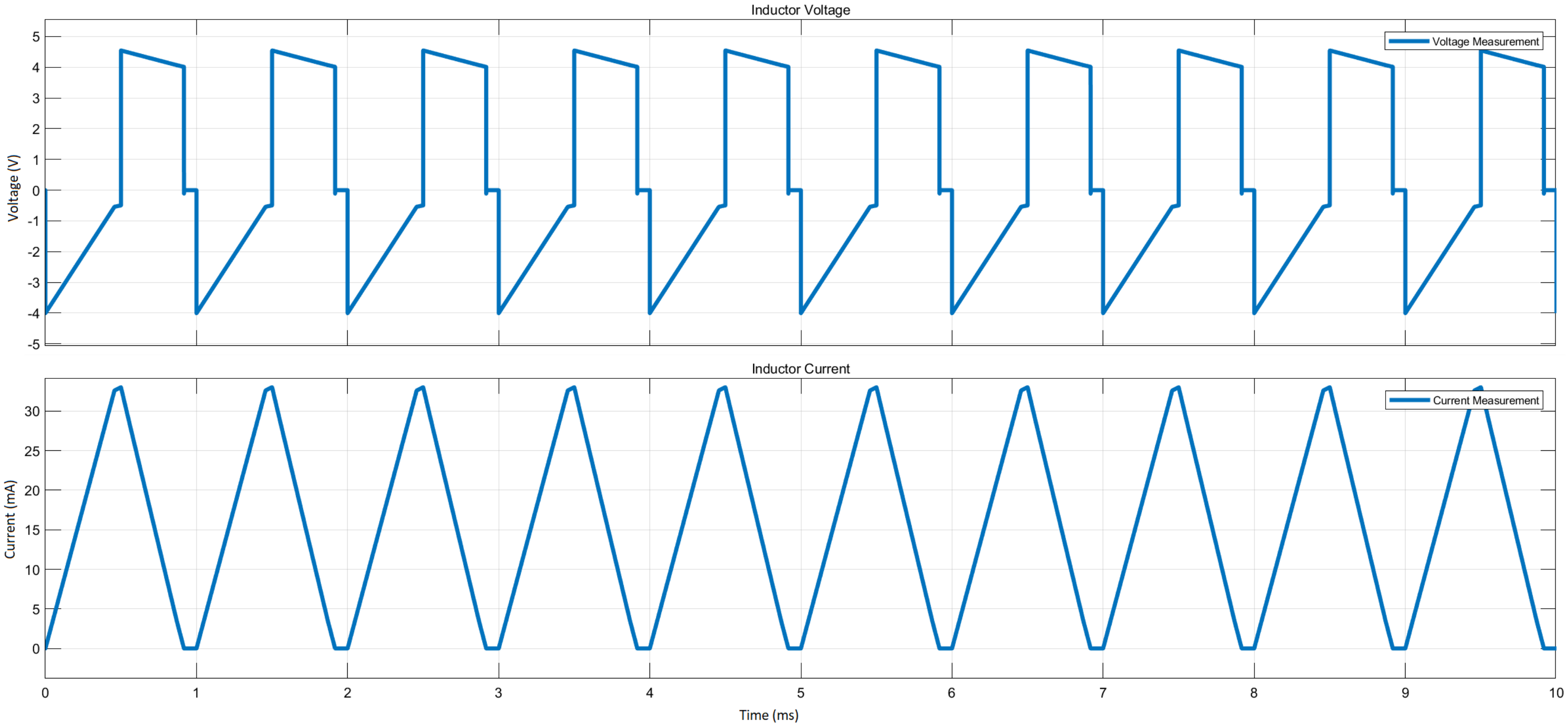

Figure 31: Inductor voltage and current plot for SOC method using FIS

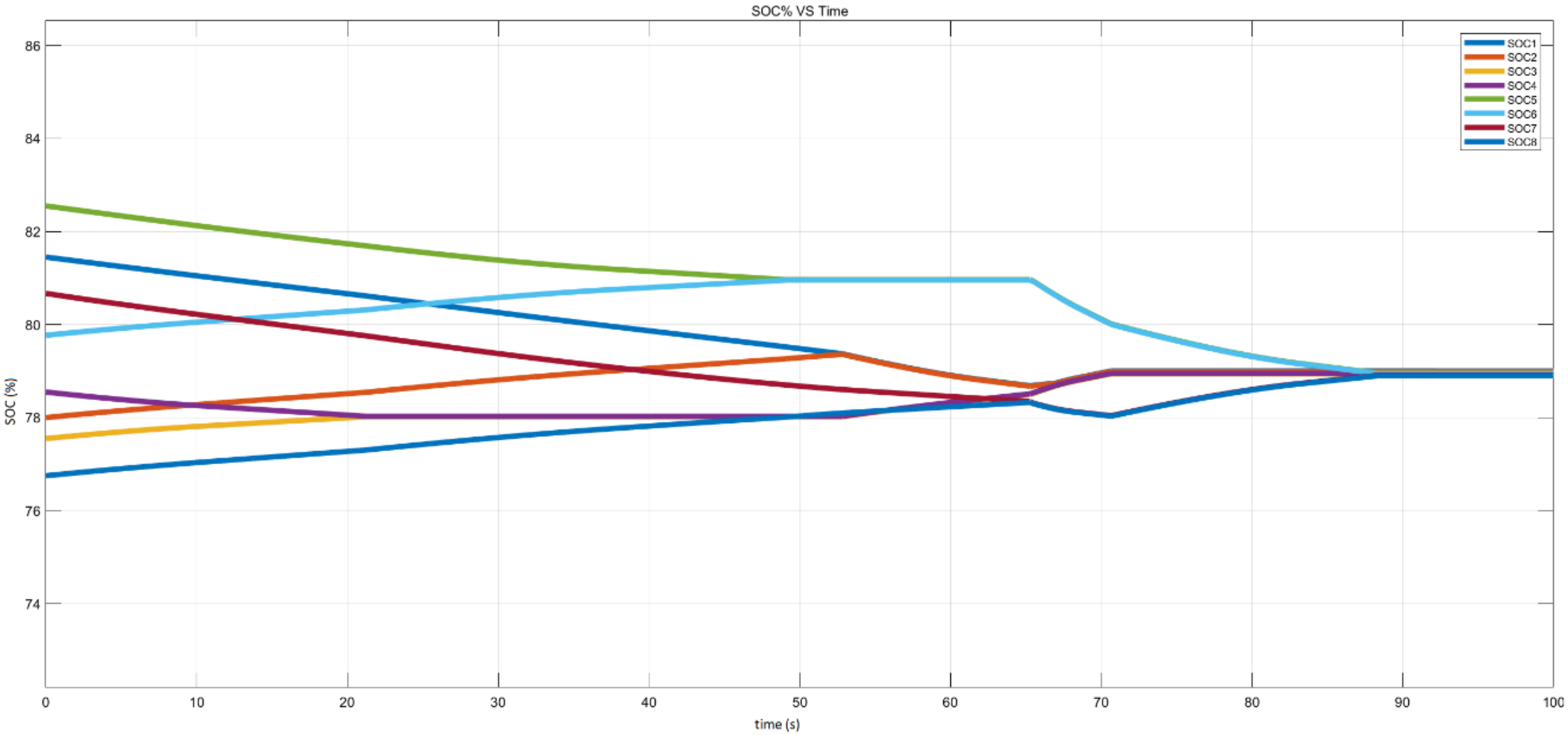

Figure 32: Cell SOC balancing status for SOC method using FIS

5.3 Method 3

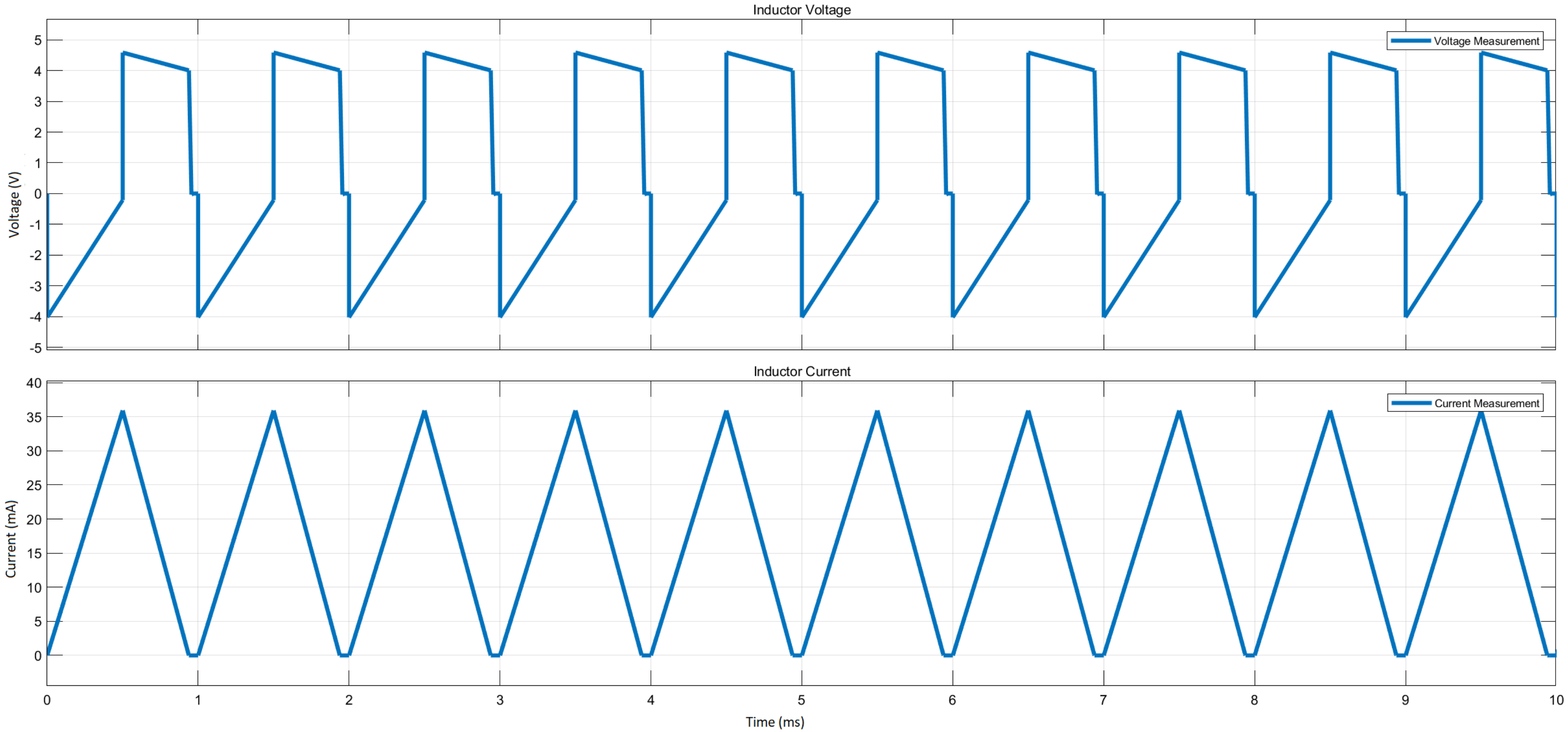

Figure 33: Inductor voltage and current plot for SOC method using ANFIS

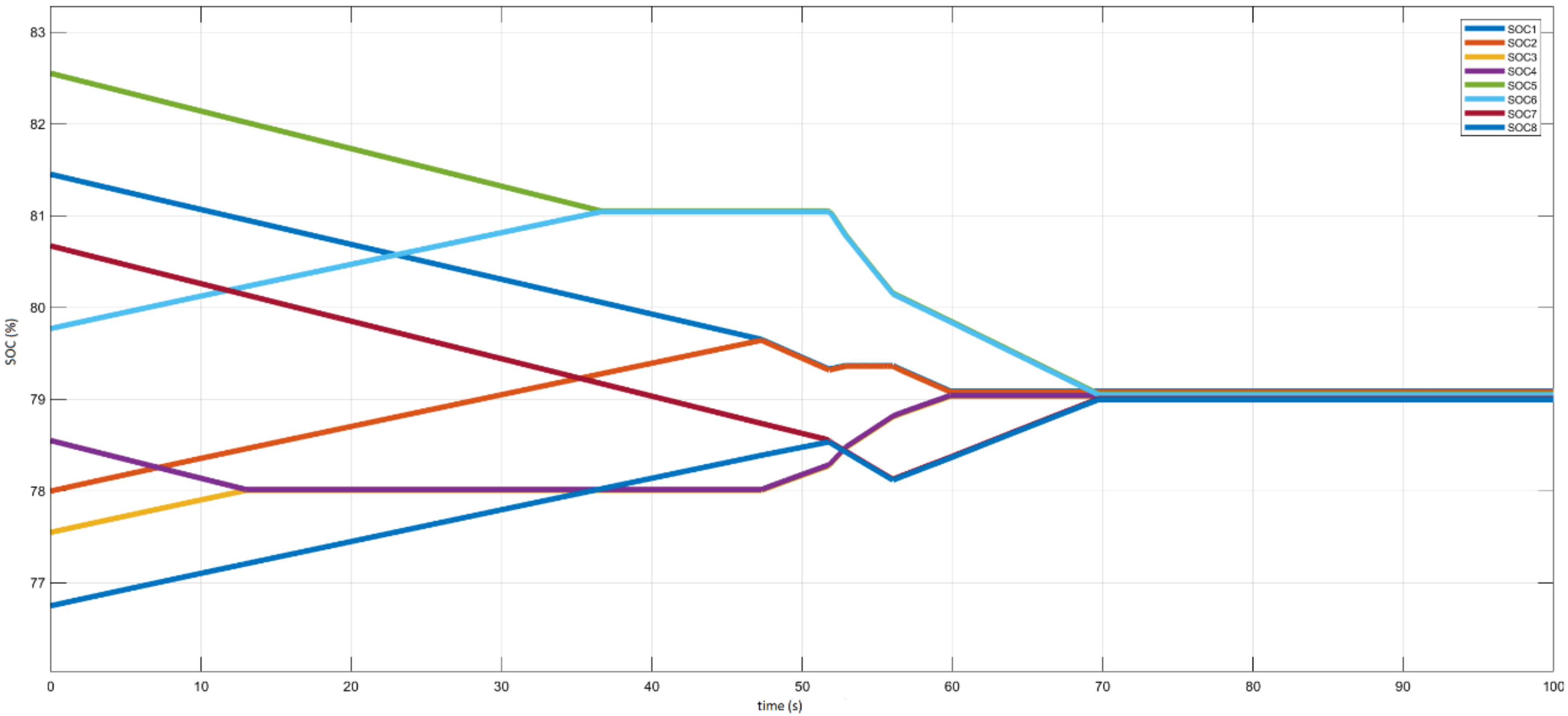

Figure 34: Cell SOC balancing status for SOC method using ANFIS

In our study, we divided the cell balancing process into three stages. Each stage focuses on balancing specific pairs of cells until their deltaSOC(dSOC) values reach the specified thresholdSOC(thSOC) value. In the first stage, individual cell pairs are balanced. This means that cell 1 and cell 2, cell 3 and cell 4, cell 5 and cell 6, and cell 7 and cell 8 are balanced separately in their respective pairs. The balancing algorithm is applied to each pair until the dSOC value of the pair reaches the thSOC value. Once each pair passes the thSOC condition, we check if the dSOC values of the combined pairs, such as cell 1_2 and cell 3_4, cell 5_6 and cell 7_8, are below the thSOC value. If they are not, the balancing process continues for the next set of paired cells until the condition is met. After that, the last stage involves balancing pairs of four cells. The balancing algorithm is applied to pairs such as cell 12_34 and cell 56_78 until the SOC values of these pairs reach the thSOC value.

The time taken for each individual balancing stage is discussed in the following section of the report, providing more detailed information on the duration required for each stage.

5.4 Balancing Time Stage-wise Comparison Table

Type of Model	Stage 1 Time(s)	Stage 2 Time(s)	Stage 3 Time(s)	Balance Time(s)
Voltage Method	92.43	94.16	96.28	> 200
FIS Method	67.75	71.55	88.22	88.22
ANFIS Method	52	56.13	69.31	69.31

Table 2: Balancing time comparison

5.5 Balancing Time Comparison Chart

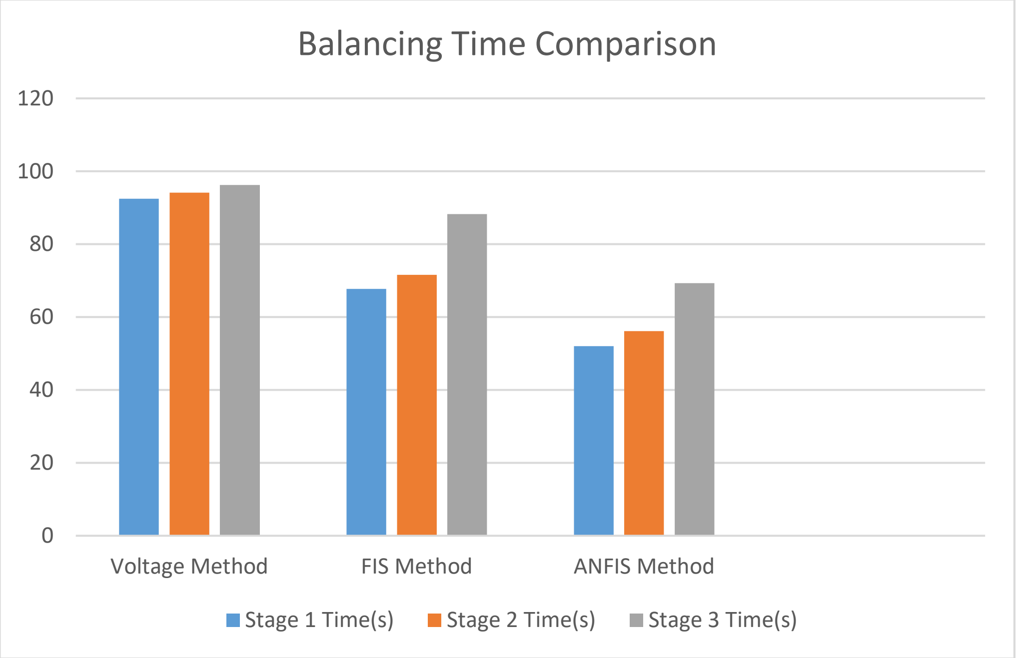

Figure 35: Comparison of balancing time for different methods

The results of our study indicate that the ANFIS-based cell balancing approach achieves faster balancing of all the cells up to the specified deltaSOC level compared to other methods. This can be attributed to the adaptive nature of the ANFIS algorithm, which learns from previous data. In our case, the algorithm maps nine output membership functions, allowing it to infer and select the closest output based on the training data. This selected output is then defuzzied to obtain a single crisp output, resulting in efficient cell balancing.

On the other hand, the FIS method relies on a set of user-defined membership functions and rules. It produces outputs over a wide range of values, which are not deterministic and vary as the input values change, even for small variations. This characteristic of the FIS algorithm makes it relatively slower compared to the ANFIS approach.

In the case of the voltage-based FIS method, we observed that the balancing process was not completed within the designated time frame of 200 seconds. This behaviour can be attributed to the influence of cell characteristics, as the OCV to SOC curve does not exhibit a linear relationship with voltage. Only at higher and lower SOC points, the curve tends to be linear, as illustrated in the figure above. Therefore, the direct SOC estimation based on voltage alone is not highly accurate, and this method may be more suitable for low-compute applications where complex algorithms like fuzzy systems cannot be implemented.

Overall, our study highlights the advantages of the ANFIS-based approach in achieving faster cell balancing, thanks to its adaptive nature and ability to infer from training data. However, the voltage-based FIS method may still have its applications in scenarios where computational complexity is a constraint.

6. Advantages and Disadvantages

6.1 Method 1

- **Advantages:**

1. Voltage based method is easier to implement on any system with just one parameter to measure and use for the process of balancing.
2. Does not involve complex algorithms to estimate the SOC
3. Faster in execution and low computing power.

- **Disadvantages:**

1. Due to the characteristic chemistry of the cell, the voltage may not be a linear function of capacity and hence not a good parameter to consider.
2. It works only at high and low-capacity regions where the cell capacity is almost relative to the voltage.

6.2 Method 2

- **Advantages:**

1. It is a very accurate method to perform the balancing process gauging the SOC value.
2. This method of balancing is suitable throughout the OCV/SOC curve of the cell regardless of the chemistry.
3. Exact mapping of membership functions and fuzzy rules can be given and this method.

- **Disadvantages:**

1. The algorithm is complex and requires higher computing power which makes it relatively slower.

2. A fuzzy logic controller totally depends on human knowledge and expertise. These controllers cannot recognize machine learning or neural networks.

6.3 Method 3

- **Advantages:**

1. Faster balancing process as the outputs are more deterministic and stable.
2. Captures nonlinearity of a process and has an automatic adaptation capability.
3. The flexibility of ANFIS is high so that it allows many variants.

- **Disadvantages:**

1. Requires more time to perform training and fuzzification/defuzzification.
2. Training data from a known/deterministic system is required to initiate this method.
3. A fault in the training data might make the system indeterministic and requires a good amount of data to cover edge cases.

7. Conclusion and Future Work

Through this project, we investigated and development of different active balancing strategies utilizing fuzzy inference systems and adaptive neuro fuzzy inference systems. Specifically, we focused on the utilization of voltage and SOC parameters and conducted a comparative analysis of the results obtained from these approaches.

The main findings of this study indicate that several key parameters play a crucial role in the active balancing process. Firstly, obtaining individual cell SOC values, which act as inputs to the fuzzy blocks, is essential. Additionally, determining the optimal inductor value is crucial for achieving effective balancing.

In terms of balancing speed, the results demonstrate that the voltage-based method does not exhibit complete balancing of SOC even after 200 seconds of simulation. However, using method 2, we observe a balanced SOC of 79% across all cells at 88.2 seconds. This method employs a charging mechanism from cells with lower SOC to those with higher SOC, indicating evidence of an active balancing process. Similarly, method 3 achieves a balanced SOC of 79% at 69.3 seconds, following a similar pattern as the previous method. Comparing the three methods, the ANFIS method with SOC input outperforms the others, demonstrating the shortest balancing time among all three stages to achieve a balanced cell SOC value.

Furthermore, we have developed a model-based algorithm for evaluating and studying various active balancing methods. This algorithm can be deployed on hardware targets, such as TI C2000 or STM32 microcontrollers, to test and validate its functionality. By utilizing SIMULINK model design and code generation tools, these algorithms can be seamlessly implemented on embedded targets. It is worth noting that the application of these battery algorithms holds significant potential in the battery technology industry. Our work opens up avenues for future research, including the deployment of these algorithms on hardware targets and the exploration of their broader applications in battery technology.

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9. Appendix

Appendix-A

Code used in the model's function block to make a decision for activating the balancing stage:

Algorithm:

1. Input all the SOC values to the function block
2. Define number of series cells Nc
3. Calculate average SOC using sum of all SOC divided by number of series cells
4. Initialize the gate signal values to zero
5. Calculate absolute delta SOC for each cell pair in the series string
6. Choose a delta SOC value after which the balancing process has to start in the second and third stage.

```
%This code is used to control the stagewise activation of balancing
function [G12_34, G56_78,G1234_5678] = fcn(SOC1, SOC2, SOC3, SOC4,
SOC5, SOC6, SOC7, SOC8)

Nc = 8;                         %number of cells
thSOC = 0.01;           %minimum delta SOC to start balancing
avgSOC = (SOC1+SOC2+SOC3+SOC4+SOC5+SOC6+SOC7+SOC8)/Nc;

G12_34 = 0;                     %initialise gate states to 0
G56_78 = 0;
G1234_5678 = 0;

dSOC1_2 = abs(SOC1-SOC2);     %calculating deltaSOC
dSOC3_4 = abs(SOC3-SOC4);
dSOC5_6 = abs(SOC5-SOC6);
dSOC7_8 = abs(SOC7-SOC8);
```

```
dSOC12_34 = abs(dSOC1_2 - dSOC3_4);
dSOC56_78 = abs(dSOC5_6 - dSOC7_8);

%condition to activate upper section of stage 2
if((dSOC1_2 < thSOC) && (dSOC3_4 < thSOC))
    G12_34 = 1;
end

%condition to activate lower section of stage 2
if((dSOC5_6 < thSOC) && (dSOC7_8 < thSOC))
    G56_78 = 1;
end

%condition to activate stage 3
if((dSOC12_34 < thSOC) && (dSOC56_78 < thSOC))
    G1234_5678 = 1;
end
end
```