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Active balancing charging using ANFIS to reach longest lifetime for lithium ion

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ABSTRACT

This research aims to address challenges in efficient energy storage in electric vehicles, particularly those using lithium-ion batteries. The research focuses on voltage imbalances in battery packs with cells connected in series, which can reduce the battery pack's lifespan. We investigated active balancing charging methods using bidirectional fly-back converters in both pack-to-cell and cell-to-pack modes. Current charging methods face limitations such as prolonged balancing times, circuit complexity, and low efficiency. To overcome these challenges, this research proposes integrating an artificial intelligence approach using adaptive neuro-fuzzy inference system (ANFIS) control. This approach allows for dynamic adjustment of duty cycles, expediting the balancing process. Experimental results show that employing ANFIS control can significantly reduce balancing times. In pack-to-cell mode, balancing time decreased from 660 seconds to 600 seconds, while in cell-to-pack mode, it decreased from 660 seconds to 580 seconds. This research makes a significant contribution to the development of more efficient charging technology for lithium-ion batteries in electric vehicles. Its potential implications include improved battery lifespan and electric vehicle performance in the future.

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1. INTRODUCTION

Currently, the growth of electric vehicles has been rapid, making efficiency in electrical energy storage a crucial aspect [1], [2]. Lithium-ion batteries are the preferred choice due to their high working voltage, high energy density, lack of memory effect, low self-discharge rate, and long lifespan [3]. To meet the required voltage and power capacity, batteries with cells connected in series are used [4], [5]. However, differences in the output voltage of each battery cell or voltage imbalance may occur due to variations in manufacturing processes, environmental conditions, and different charging and discharging cycles [6], [7]. When recharging series-connected battery packs, some battery cells may require additional charging even after one cell reaches full capacity [8], [9]. Battery imbalance can lead to overcharging or undercharging, significantly reducing battery life and affecting battery capacity [1], [10]. In extreme cases, battery imbalance can pose a risk to devices or even humans. Therefore, it is important to have an effective battery balancing system [11], [12].

In recent years, several battery balancing methods have been developed, with passive balancing and active balancing being the main methods [13]. Passive balancing involves the use of resistors and switches connected in parallel on each battery cell. Excess cells will dissipate energy through the resistors when the system is operational. This method not only causes energy wastage but also presents challenges in thermal management. Meanwhile, active balancing can be classified into five categories: adjacent cell to cell (AC2C), direct cell to cell (DC2C), pack to cell (P2C), cell to pack (C2P), and any cell to any cell (AC2AC). The active balancing process involves transferring energy from high-voltage batteries to low-voltage batteries. Among these categories, P2C and C2P utilize bidirectional flyback converters [14]. Beside their high efficiency, these converters also offer ease of isolation, simple control, and small size [15], [16].

Previous research has applied this approach; however, these methods still have limitations such as long balancing times, circuit complexity, and low efficiency. In this context, the use of artificial intelligence techniques, particularly adaptive neuro-fuzzy inference system (ANFIS) control, offers a more adaptive and intelligent solution compared to traditional approaches like fuzzy logic. While fuzzy logic methods can also address voltage imbalances, ANFIS provides advantages in adaptability and higher intelligence. By combining artificial neural networks and fuzzy logic, ANFIS dynamically adjusts the balancing process based on real-time data and environmental conditions. This not only enhances efficiency but also reduces the risk of overcharging or undercharging, thus extending battery life and improving overall safety. The results of the tests and comparisons will be presented in this paper.

2. METHOD

In this paper, we delve into the design and implementation of an active voltage balancing system. This system operates between cells and battery packs utilizing a bidirectional flyback converter. Furthermore, ANFIS control is integrated to regulate the balancing process effectively.

Figure 1 shows that there are four battery cells connected in series. Each battery cell is paralleled with a voltage sensor that provides feedback to the microcontroller [13]. This feedback is used to control the duty cycle in the bidirectional flyback converter circuit. Each battery cell is connected to four relays, or two pairs of positive and negative relays. One pair of relays is connected to the left side of the converter as a battery pack, and the other pair is connected to the right side of the converter as a battery cell. The relays act as switches to regulate the battery cell as a source or load, or as a battery pack or cell. The bidirectional flyback converter is used to achieve the balancing function with a simpler structure.

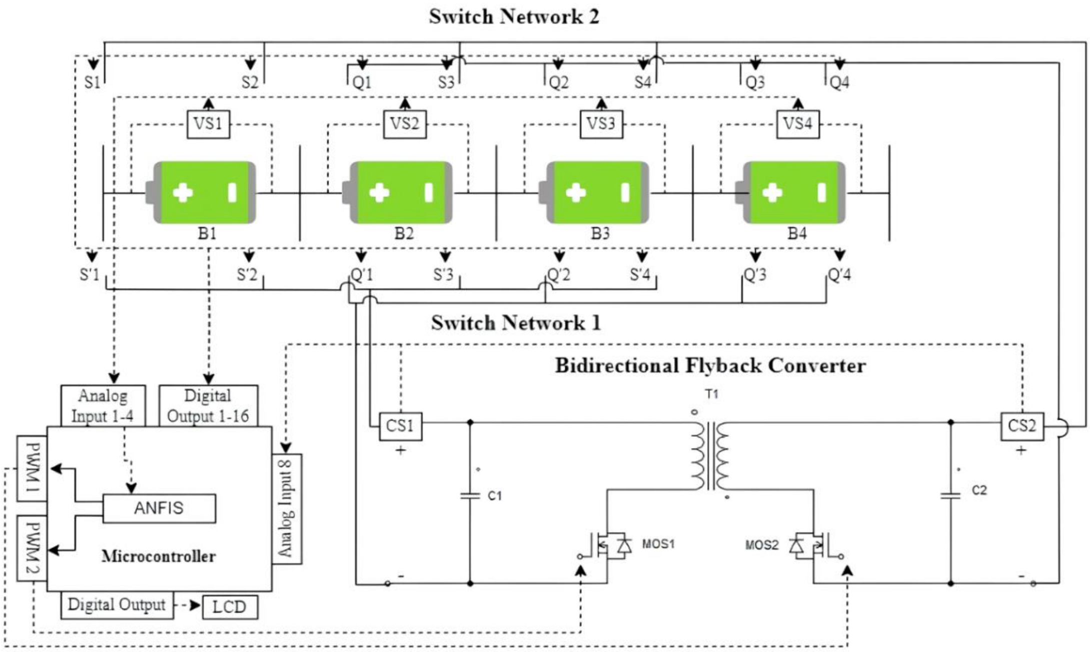


Figure 1. Block diagram system

2.1. Balancing system

The system's balancing process is divided into two modes: from the battery pack to the cell and from the cell to the battery pack. When operating in pack-to-cell mode, or conversely, cell-to-pack mode, this battery pack, which consists of four series-connected battery cells, channels power from three cells to one other cell, or vice versa. This configuration is illustrated in Figure 2.

Figure 2. displays the flowchart for the balancing system. Initially, voltage readings are taken from each sensor in every battery cell. The average voltage value of the entire battery is then calculated. A comparison is made to determine if any of the battery cells in batteries 1, 2, 3, or 4 have a voltage value greater than the average. If so, that battery will be used as a source. Meanwhile, if any of the battery cells 1, 2, 3, or 4 has a voltage value lower than the average voltage value, it will be used as a load. In other words, if only one battery cell voltage is lower than the average voltage, then the pack-to-cell mode will operate, and vice versa, if only one battery cell voltage is higher than the average voltage, then the cell-to-pack mode will operate. These two modes will alternate [11].

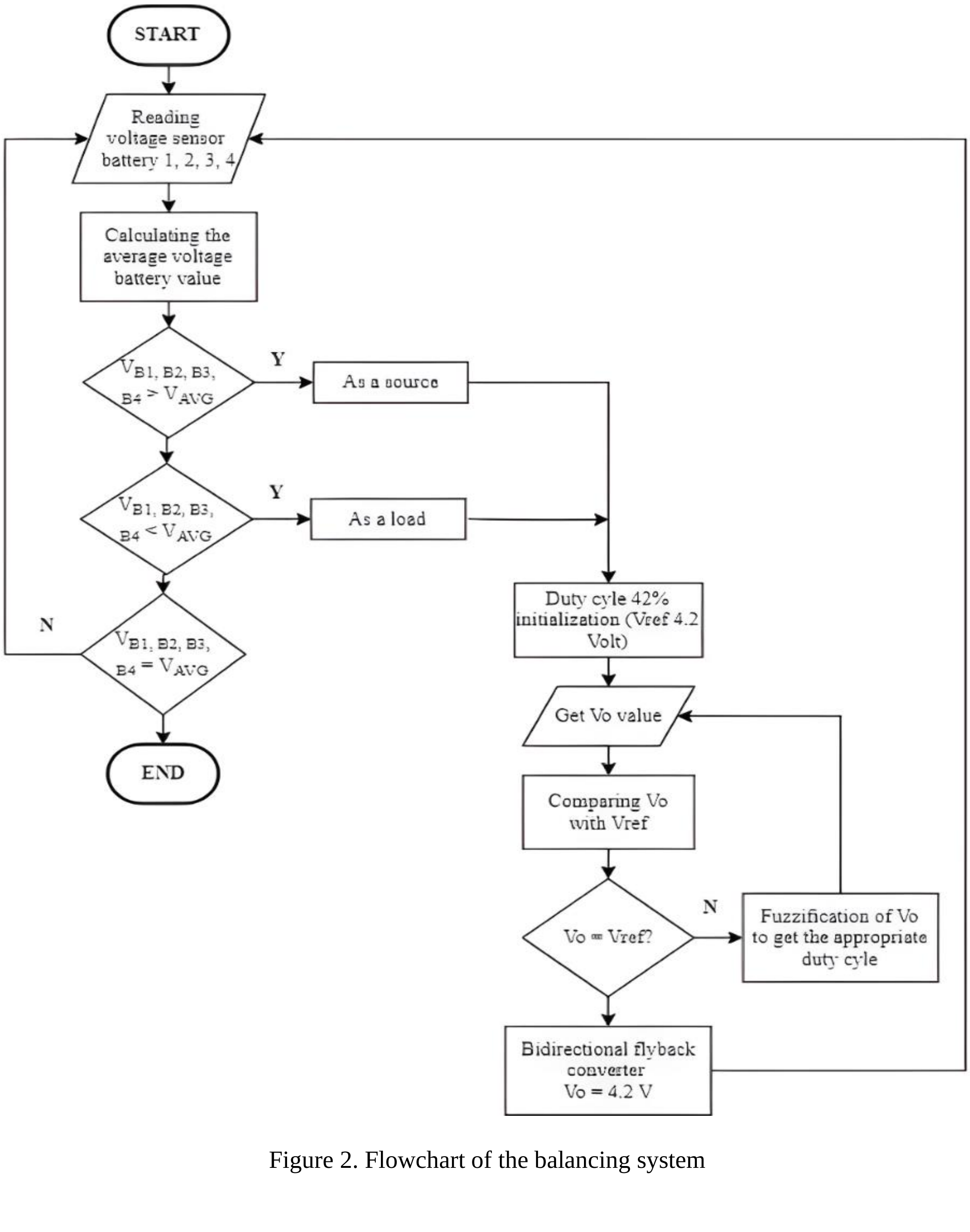


Figure 2. Flowchart of the balancing system

2.2. Sequential switch

Table 1 shows the sequential switches to be used in this system. S'1 to S'4 and Q'1 to Q'4 will connect the balancing circuit with the battery pack on the left side of the converter. S1 to S4 and Q1 to Q4 will connect the balancing circuit with the battery cells on the right side of the converter. In Table 1 for information number 1 if the battery is an active source, 0 if the battery is an active load, and tick if switch network 1 and switch network 2 are connected.

Table 1. Sequential switch

Left side battery				Right side battery				Switch network 1								Switch network 2							
B1	B2	B3	B4	B1	B2	B3	B4	S’1	S’2	S’3	S’4	Q’1	Q’2	Q’3	Q’4	S1	S2	S3	S4	Q1	Q2	Q3	Q4
1	1	1	-	-	-	-	0	√	-	-	-	-	-	√	-	-	-	-	√	-	-	-	√
-	1	1	1	0	-	-	-	-	√	-	-	-	-	-	√	√	-	-	-	√	-	-	-
0	0	0	-	-	-	-	1	√	-	-	-	-	-	√	-	-	-	-	√	-	-	-	√
-	0	0	0	1	-	-	-	-	√	-	-	-	-	-	√	√	-	-	-	√	-	-	-

2.3. Bidirectional flyback converter modeling

To achieve bidirectional balancing, the implemented system replaces the rectifier diodes in conventional flyback converters with synchronous rectifier MOSFETs [17] and reduces the losses caused by the output rectifier diodes [11]. This enhancement significantly improves the efficiency of the system. The complete converter circuit demonstrating these modifications is depicted as in Figure 3.

The planned balancing circuit consists of a transformer and two MOSFETs [18]. This converter operates in both pack-to-cell and cell-to-pack modes. For instance, in pack-to-cell mode, the balancer enters this mode of operation since the pack has a higher capacity. As illustrated in Figure 3. MOS1 is turned on while MOS2 is turned off, and the pack energy is stored in the magnetizing inductor Lm. Then, MOS2 is turned on while MOS1 is turned off. Currently, the energy stored in the magnetizing inductor is transferred to the secondary winding to charge the battery cell. The opposite occurs in cell to pack mode [19]. Tables 2 and 3 provide the values for each component parameter used in this converter.

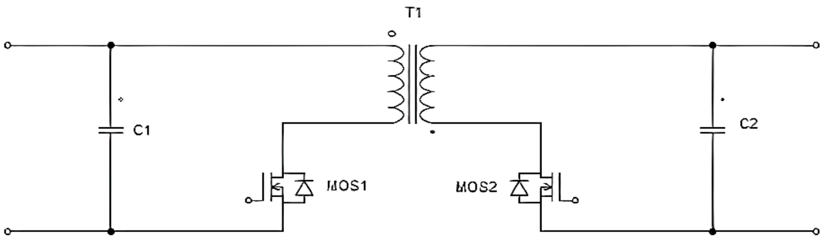


Figure 3. Bidirectional flyback converter circuit

Table 2. Flyback converter parameter for pack-to-cell mode

Parameter	Value	Unit
Vs (input voltage) (max)	12.6	Volt
Vs (min)	10.8	Volt
Vo (output voltage)	4.2	Volt
Io (output current)	2.8	Ampere
Po (output power)	11.76	Watt
Dmax (maximum duty cycle)	50	%
Fs (switching frequency)	100	Hertz
Lm (magnetizing inductance)	22	µHenry
Np:Ns (transformer turns ratio)	4:2	winding
Co (output capacitance)	4700	µFarad

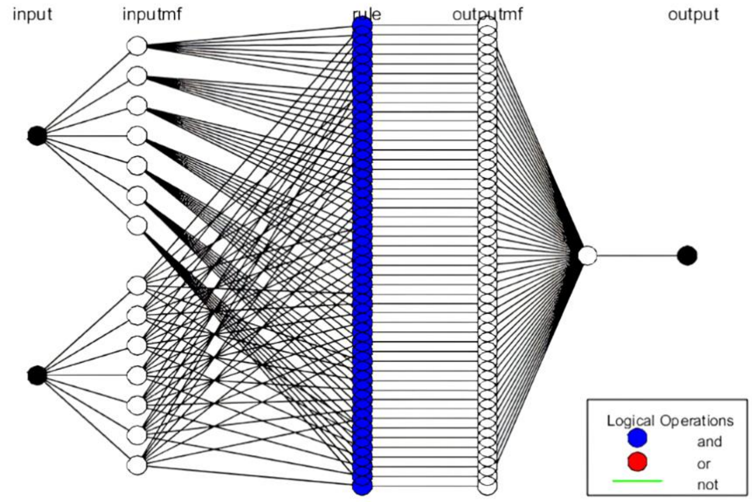
Table 3. Flyback converter parameter in cell-to-pack mode

Parameter	Value	Unit
Vs (input voltage) (max)	4.2	Volt
Vs (min)	3.6	Volt
Vo (output voltage)	12.6	Volt
Io (output current)	2.8	Ampere
Po (output power)	35.28	Watt
Dmax (maximum duty cycle)	90	%
Fs (switching frequency)	100	Hertz
Lm (magnetizing inductance)	2.7	µHenry
Np:Ns (transformer turns ratio)	4:2	winding
Co (output capacitance)	2200	µFarad

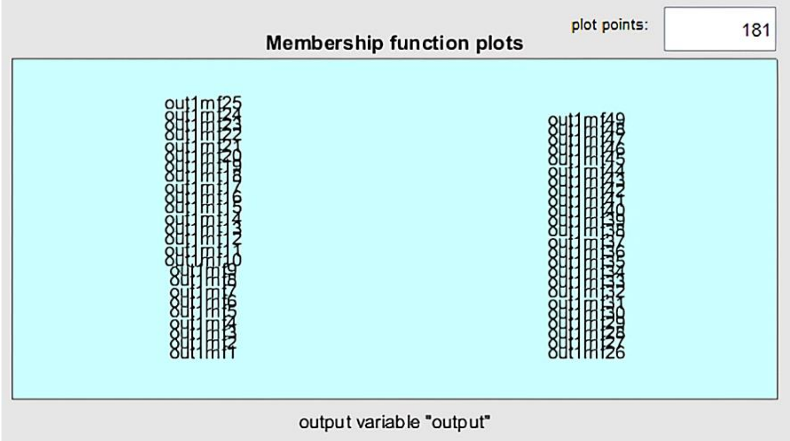
2.4. ANFIS control modeling

ANFIS control combines the learning capabilities of neural networks with the decision-making of fuzzy control [20], [21]. The purpose of this combination is to optimize the advantages of each control and reduce their shortcomings, resulting in ANFIS being a control system that belongs to the adaptive network category [22]. The control system can adjust or adapt to the data and conditions present in the system [23].

ANFIS uses a set of data derived from the fuzzy control inputs and outputs generated by the ongoing system simulation. This data is then used as a training dataset to achieve the desired error rate. When designing ANFIS control, it is possible to adjust the number and type of membership functions as needed [24]. In this case, 7x7 membership functions are used because a greater number of membership functions results in a smaller error. Additionally, the training process uses a hybrid method that combines the least squares estimator (LSE) and error back propagation (EBP) method [25], which is carried out over a thousand iterations. It is expected that the error value will decrease and the resulting training data will improve with each iteration. Test results are shown in Figures 4(a)-4(c).



(a)



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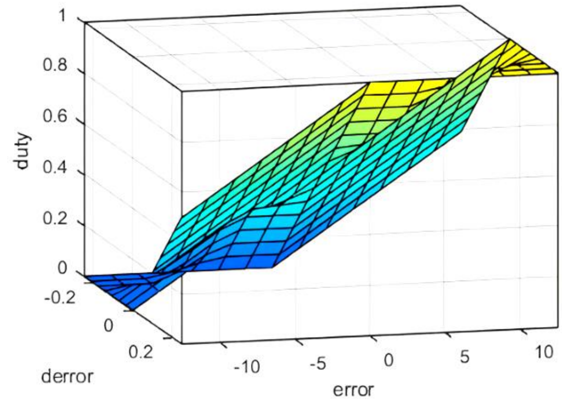

(c)

Figure 4. ANFIS control modeling: (a) ANFIS structure, (b) variable duty cycle output, and (c) ANFIS structure viewer

2.5. Open loop simulation modeling

The simulation's parameter values are adjusted to match the calculation results. PSIM 2022 software is used for this simulation. Figure 5 displays the system simulation circuit in both pack-to-cell and cell-to-pack modes. In this simulation, the duty cycle value is manually set. Specifically, the duty cycle value is set at 43.03% for pack-to-cell mode and 63.12% for cell-to-pack mode, as determined by the system requirements. These values are crucial for determining the performance of the balancing system under different operational conditions.

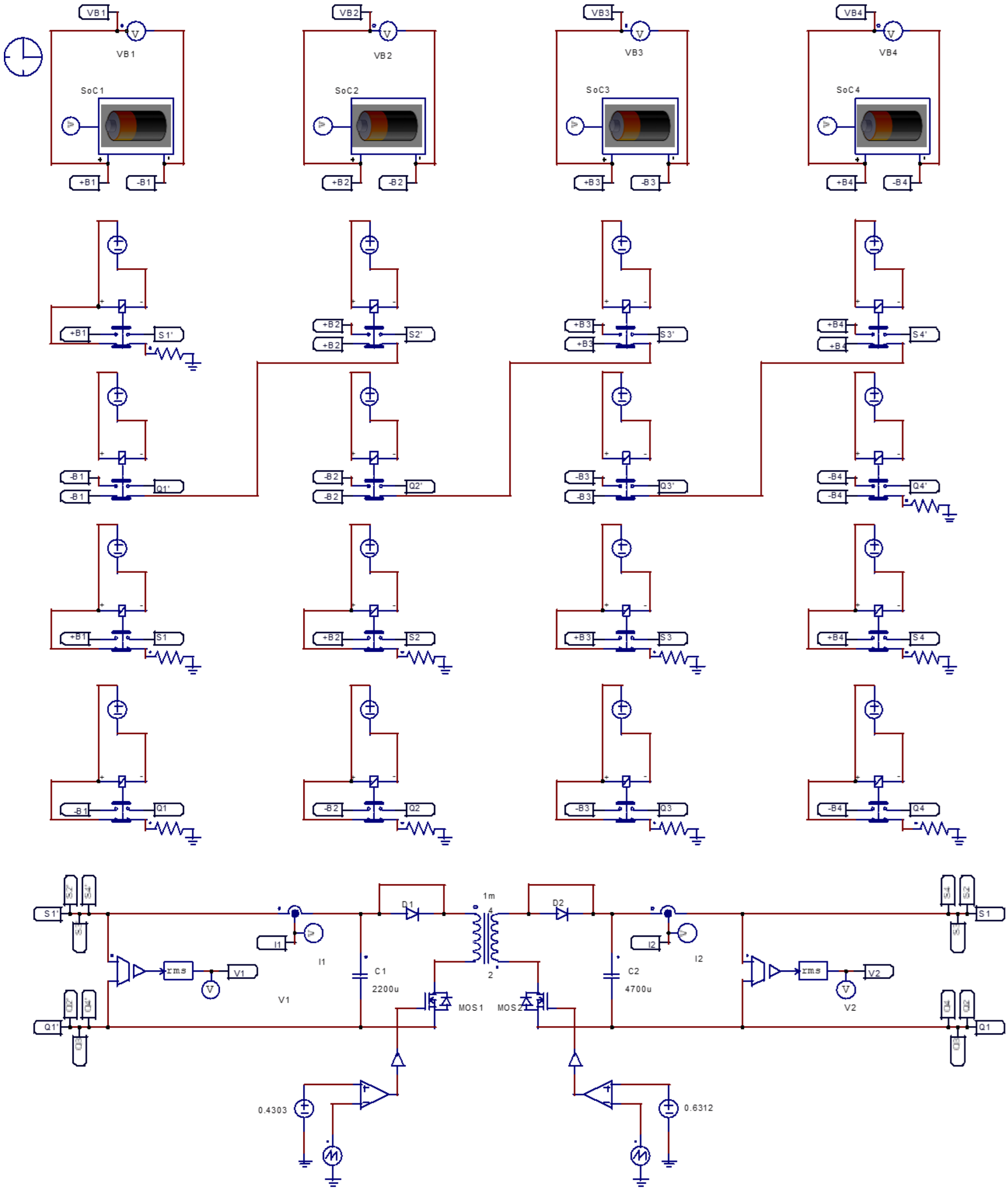

Figure 5. Open loop simulation circuit

2.6. Simulation modeling of closed-loop integration

Closed-loop integration simulation (closed circuit) is a simulation of the entire system using ANFIS control. The parameter values used for the simulation are adjusted to the calculation results. The simulation was conducted using PSIM 2022 software. Figure 6 shows the system simulation circuit in pack-to-cell and cell-to-pack modes.

This simulation utilizes ANFIS to provide feedback in the form of duty cycle. The duty cycle is obtained by integrating real-time Vo readings with the set point voltage value, which is set to produce the desired output. The aim is to improve upon the open loop simulation (without control).

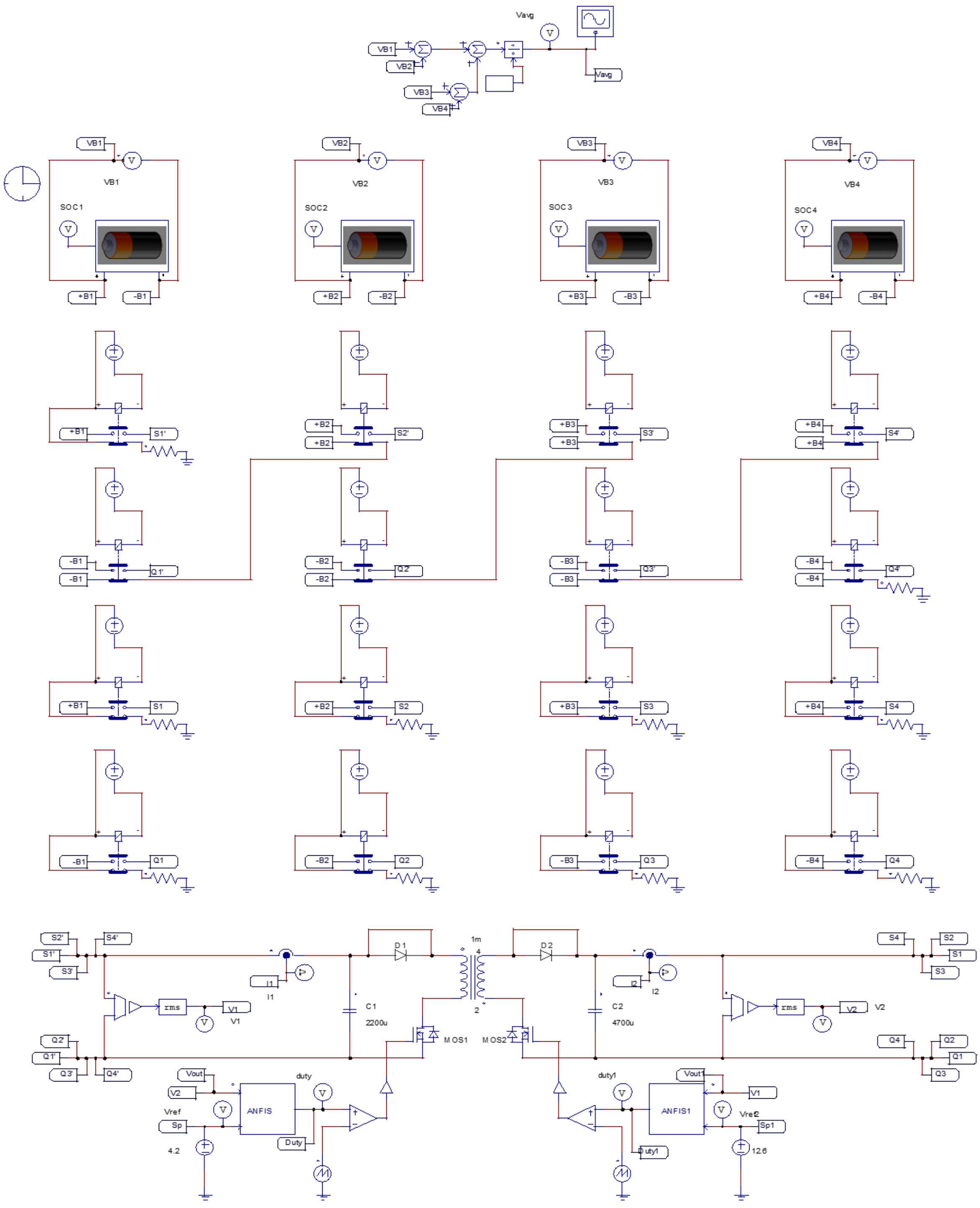

Figure 6. Close loop integration simulation circuit

3. RESULTS AND DISCUSSION

The simulations were conducted using PSIM 2022 software in both pack-to-cell and cell-to-pack modes. After performing open-loop simulation and closed-loop integration, the system's performance was evaluated. The obtained results provide insights into the effectiveness of the proposed approach.

3.1. Open loop simulation testing

Following open loop simulation testing, the test results are presented as the voltage of each cell, namely VB1, VB2, VB3, and VB4, before and after balancing. These results are crucial for evaluating the performance of the balancing system. For further details and comprehensive analysis, as in Tables 4 and 5.

Table 4 shows the results of open loop simulation testing in pack to cell mode. Initially, the voltage of batteries 1, 2, and 3 was higher than the average voltage, and therefore they were used as a source, forming a series-connected battery pack. Regarding the battery voltage, 4 is lower than the average voltage and is therefore used as a load. This can be considered balanced because the voltage of each battery was the same for a balancing time of 660 seconds. The simulation test results for each battery voltage can be seen in Figure 7.

Table 5 shows the results of open loop simulation testing in cell to pack mode. Initially, batteries 1, 2, and 3 had a voltage lower than the average, so they were used as a load, forming a series-connected battery pack. Battery 4 had a voltage higher than the average, so it was used as a source. This can be considered balanced because the voltage of each battery was the same for a balancing time of 660 seconds. Figure 8 shows the simulation test results for each battery voltage.

Table 4. Test results for open loop simulation of pack to cell mode

Parameter	Before balancing	After balancing	Unit
VB1	4.222	4.149	Volt
VB2	4.222	4.149	Volt
VB3	4.222	4.149	Volt
VB4	3.942	4.149	Volt

Table 5. Test results for open loop simulation of cell to pack mode

Parameter	Before balancing	After balancing	Unit
VB1	3.942	4.008	Volt
VB2	3.942	4.008	Volt
VB3	3.942	4.008	Volt
VB4	4.222	4.008	Volt

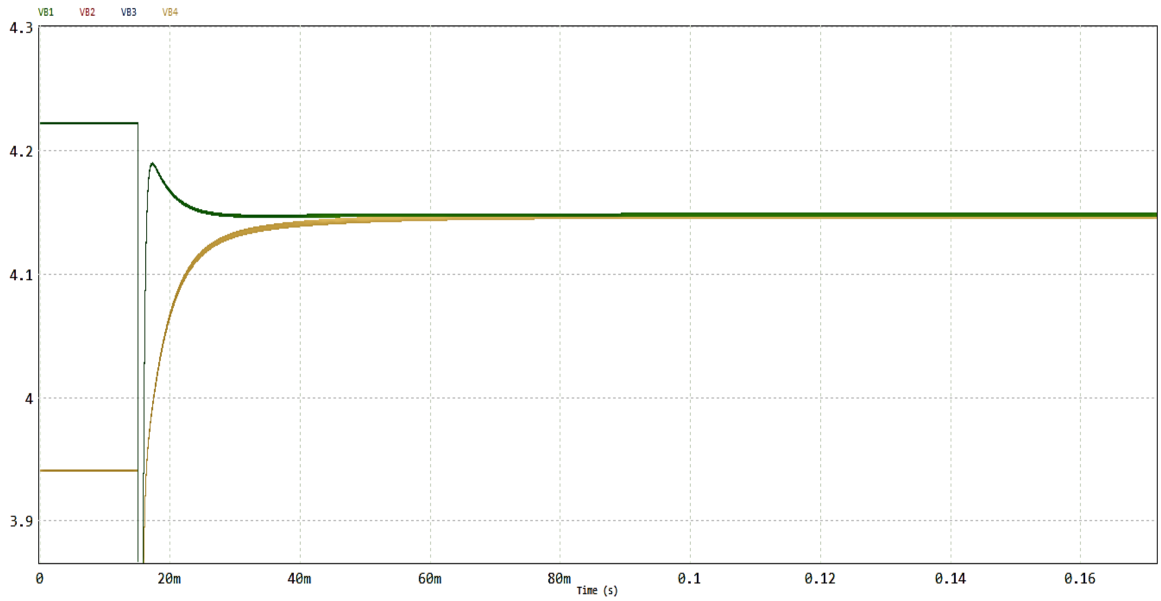

Figure 7. Open loop simulation test results of pack to cell mode graph (horizontal axis: time (s), vertical axis: battery voltage (V))

3.2. Simulation testing of closed loop integration

Following the close loop integration simulation testing, test results were obtained in the form of the voltage of each cell, namely VB1, VB2, VB3, and VB4 before and after balancing. The results are presented in Tables 6 and 7. These tables provide a detailed overview of the voltage levels and the effectiveness of the balancing process. Table 6 shows the results of the close loop integration simulation testing in pack to cell mode. Initially, the voltage of batteries 1, 2, and 3 was higher than the average voltage, making them a suitable source, namely a series-connected battery pack. Regarding the battery voltage, 4 is lower than the average voltage, so it is utilized as a load. This can be considered balanced because the voltage of each battery was the same for a balancing time of 600 seconds. The simulation test results for each battery voltage can be observed in Figure 9.

Table 7 shows the results of the closed-loop integration simulation testing in cell-to-pack mode. Initially, batteries 1, 2, and 3 had a voltage lower than the average voltage, so they were used as a load, forming a series-connected battery pack. Battery 4 had a voltage higher than the average, so it was used as a source. This can be considered balanced because the voltage of each battery was the same for a balancing time of 580 seconds. Figure 10 shows the simulation test results for each battery voltage.

Table 6. Simulation testing results of closed-loop integration of pack-to-cell mode

Parameter	Before balancing	After balancing	Unit
VB1	4.126	4.078	Volt
VB2	4.126	4.078	Volt
VB3	4.126	4.078	Volt
VB4	3.937	4.078	Volt

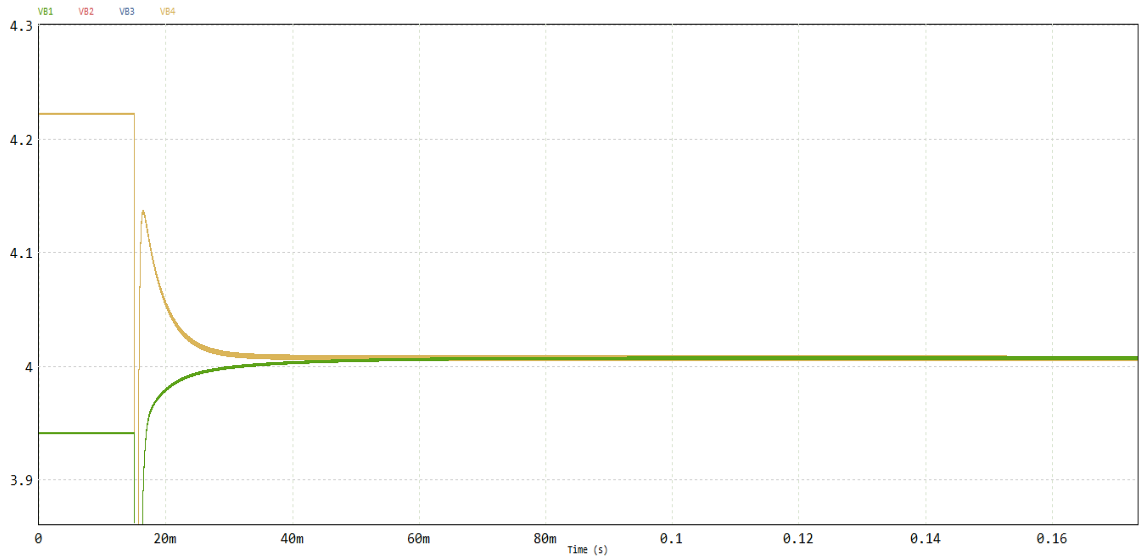

Figure 8. Open loop simulation test results graph for cell-to-pack mode
(horizontal axis: time (s), vertical axis: battery voltage (V))

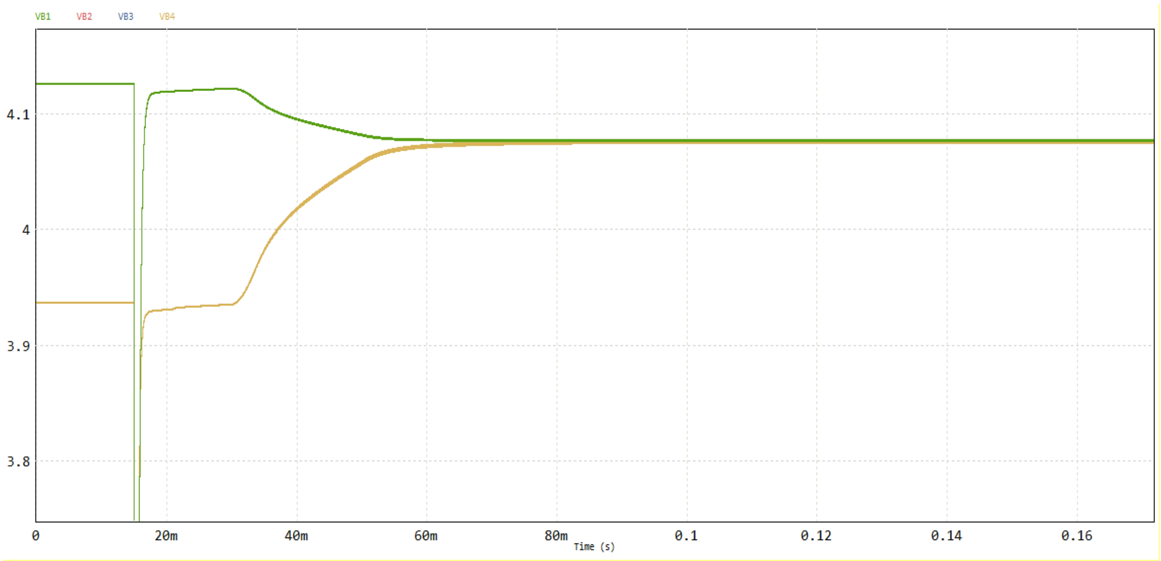

Figure 9. Graph of simulation test results for closed-loop integration of pack-to-cell mode
(horizontal axis: time (s), vertical axis: battery voltage (V))

Table 7. Simulation testing results of closed loop integration of cell to pack mode

Parameter	Before balancing	After balancing	Unit
VB1	3.942	3.994	Volt
VB2	3.942	3.994	Volt
VB3	3.942	3.994	Volt
VB4	4.158	3.994	Volt

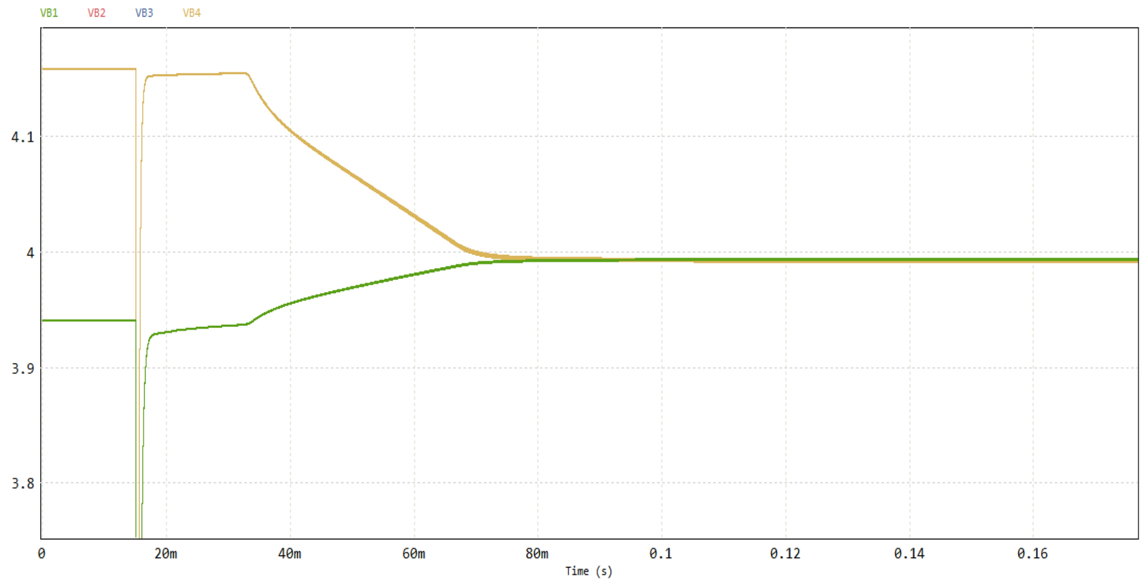

Figure 10. Graph of simulation test results for closed-loop integration from cell to pack mode (horizontal axis: time (s), vertical axis: battery voltage (V))

3.3. Comparison of open loop simulation and closed loop integration test results

The test results for the open loop simulation without control and the closed loop integration simulation using ANFIS control are shown above. The balancing times for each mode are presented. A comparison was made between simulations with and without control, and the results are shown in Table 8.

After conducting simulations and closed-loop integration using PSIM 2022 software, the obtained results indicate that the use of adaptive neuro-fuzzy inference system (ANFIS) control has a significant impact on the battery voltage balancing time. In the pack to cell mode simulation, the balancing time with ANFIS control is 600 seconds, whereas without ANFIS control, it requires 660 seconds. Similarly, in the cell to pack mode simulation, the balancing time with ANFIS control is 580 seconds, whereas without control, it requires the same time as the previous mode, which is 660 seconds.

The interpretation of these results indicates that the use of ANFIS control significantly accelerates the battery voltage balancing process, reducing the time required to achieve the desired level of balance. This has important implications in practical applications, especially in electric vehicles where battery efficiency and performance are crucial. By speeding up the balancing time, ANFIS control can enhance battery charging efficiency, extend battery life, and ultimately improve the overall performance and durability of electric vehicles.

Table 8. Comparison of simulation test results

Mode	Control	Balancing time (s)
Pack to cell	Without control	660
	With ANFIS	600
Cell to pack	Without control	660
	With ANFIS	580

4. CONCLUSION

Overall, this study addresses challenges associated with efficient energy storage in electric vehicles, with a specific focus on lithium-ion batteries. The primary investigation revolves around voltage imbalances in series-connected battery packs, a factor known to compromise the overall battery pack lifespan. Active balancing methods are explored, utilizing bidirectional flyback converters in configurations from both pack to cell and cell to pack. These methods aim to overcome common limitations in existing charging techniques, including lengthy balancing times, circuit complexity, and suboptimal efficiency.

To address these challenges, the study proposes the integration of an artificial intelligence approach through adaptive neuro-fuzzy inference system (ANFIS) control. This innovative methodology facilitates dynamic adjustment of duty cycles, thus significantly expediting the balancing process. Experimental findings affirm the effectiveness of ANFIS control, demonstrating a significant reduction in balancing time. Specifically, in pack-to-cell mode, the balancing time decreased from 660 seconds to 600 seconds, while in cell-to-pack mode, it decreased from 660 seconds to 580 seconds.

Essentially, this Packs", in research presents a simulation model for a balancing system aimed at enhancing battery performance and reliability. By leveraging active balancing techniques and integrating ANFIS control, the proposed system offers promising prospects for advancing lithium-ion battery charging technology in electric vehicles. The results are expected not only to improve battery lifespan but also to enhance electric vehicle performance in the future.

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