JAREE (2026), Vol. 10, No. 1
doi: 10.12962/jaree.xyzxyz

JAREE Journal on Advanced Research in Electrical Engineering
ISSN: 2579-6216

RESEARCH ARTICLE

Battery Equalization Strategy Based On Cuk Converter Using Fuzzy-PI Control

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Received: 16 June 2025; **Revised:** 23 July 2025; **Accepted:** 23 July 2025

Abstract

Inconsistencies in series-connected batteries are among the factors that affect performance and reduce battery lifespan. To ensure that the cells within a series battery pack have the same energy charge rate and to maximize the overall capacity, a battery equalizing component is necessary. However, conventional equalizing methods that rely on voltage as the control variable have a weakness; when the voltage difference or gap between batteries is small, the equalizing current supplied is also small, which in turn affects the equalizing speed. To solve this problem, this research proposes a design of an active equalizing circuit based on a Cuk converter with bidirectional energy transfer, using State of Charge (SOC) as a control variable to overcome the limitations of traditional equalizing methods that combine a Fuzzy Logic Controller (FLC) with Proportional Integral (PI) control. The simulation results of the equalizing experiment of 3 lithium batteries compared with the conventional method show the proposed scheme provides performance significantly reducing the equalizing time and providing a dynamic equalizing current regulation mechanism that adapts to various battery conditions. In the idle condition, the proposed FLC-PI algorithm reaches the balanced point in 300 seconds and in the discharging-charging condition, it takes 289 seconds. While, the conventional method, during the simulation period of 0-350 seconds, has not yet reached the balanced point.

Keywords: battery equalizing, CUK equalizer, fuzzy logic controller, PI.

I. Introduction

In recent years, electric vehicles have played a pivotal role in supporting the transition to net-zero emissions in the future, due to their low levels of pollution[1]. The cost of electric vehicles is influenced by various factors, the most significant component of which is the cost of the battery. Currently, lithium batteries are the main choice as an energy storage medium in electric vehicles[2]. In practice, lithium batteries arranged in series are commonly applied in electric vehicles and as energy storage units in renewable energy systems[3]. However, production inconsistencies, environmental differences, degradation over time, and varying system characteristics can cause imbalances between cells in a battery pack [4]. These imbalances can increase over time and indirectly reduce the battery capacity and overall battery lifetime [1][5]. Various battery equalization techniques have been widely researched in recent years to overcome the Inconsistency problem in batteries arranged in series. Currently, the most commonly used techniques for equalizing are categorized into two main types: the passive equalization technique and the active equalization technique [6].

Passive equalizing techniques generally utilize resistors as the equalizing medium, converting excess energy from a cell into heat to equalize it with the other cells. This technique has been commonly applied in electric vehicles [6][7]. However, the passive equalizing technique is considered less efficient because it does not involve energy transfer, resulting in the total battery capacity not being optimally utilized and being limited by the battery cell with the lowest capacity[8]. In contrast to passive equalizing techniques, active equalizing works by transferring excess energy using special electronic circuits, allowing maximum utilization of battery capacity.[8][9]. However, as more components are added to the equalizing circuit, the cost increases. In practice, the cost of electric vehicles becomes a primary concern for equalizing systems. One way to reduce high costs is by minimizing the number of components used, which necessitates the adoption of more advanced equalizing techniques[10].

The safe and effective operation of a battery equalizing system is not only determined by the reliability of its hardware circuit, but also depends on the equalizing control strategy, which is very important in improving system performance [11]. This strategy involves selecting the variables used as equalizing references and the appropriate control techniques. There are two main variables in battery equalizing is voltage and SOC [12]. Voltage is the most commonly used variable because it is easy to apply in practice. However, Li-ion batteries have a voltage curve that tends to be flat in the middle range of SOC, which results in voltage changes not always accurately describing battery capacity. Therefore, equalizing techniques that only rely on voltage as a equalizing parameter may not be able to fully overcome the capacity imbalance between battery cells [11][12].

This paper proposes an active equalizing circuit using SOC as the control variable with a Cuk converter circuit featuring a bidirectional energy transfer mechanism, governed by a fuzzy-PI control strategy. This control system utilizes

How to cite: Prasetia, B. D., Riawan, D. C., & Lystianingrum, V. (2026). Battery Equalization Strategy Based On Cuk Converter Using Fuzzy-PI Control. JAREE (Journal on Advanced Research in Electrical Engineering), Volume 10 (No.1).

Pulse Width Modulation (PWM) input signals to modulate the equalizing current whenever an imbalance occurs between cells, thereby adjusting the equalizing current in response to the battery conditions and enhancing faster energy transfer. Section 2 Method discusses the system of circuit, operational principles, discusses the circuit scheme and system configuration for equalizing proposed. Section 3 results and discussion show the simulation test results and the analysis. Section 4 provides the conclusions of this paper.

II. Methods

In this section, we will explain the research design stages, which include equalizing circuit scheme analysis, equalizing strategy, FLC-PI control strategy design. The analysis of the equalizing circuit scheme explains the basic operation of equalizing using a Cuk converter as a equalizing topology. The design stage of the FLC-PI control strategy includes an explanation of the scheme and working principle, and determination of the value of the equalizing control variable using fuzzy control algorithms (FLC) and Proportional Integral (PI).

A. EqualizingCircuit

The equalizing circuit described in this study is shown in Fig. 1. In the proposed system, it consists of three battery cells arranged in series with an adjacent cell-to-cell architecture approach (A-C2C) that implements a Cuk converter topology as the equalizing circuit. The proposed Cuk converter circuit consists of four inductors(*L1,L2,L3,L4*) and two capacitors(*C1,C2*) that act as energy transfer media, and four MOSFETs(*Q1,Q2,Q3,Q4*) that serve as control switches to control the equalizing current of the energy transfer mechanism using a fuzzy control strategy combined with PI controlling. The output of the FLC-PI controller is in the form of a dutycyle which functions as a PWM input to control the mosfet which serves as a control switch of the equalizing current when there is a difference in capacity between cells obtained from the battery state collector.

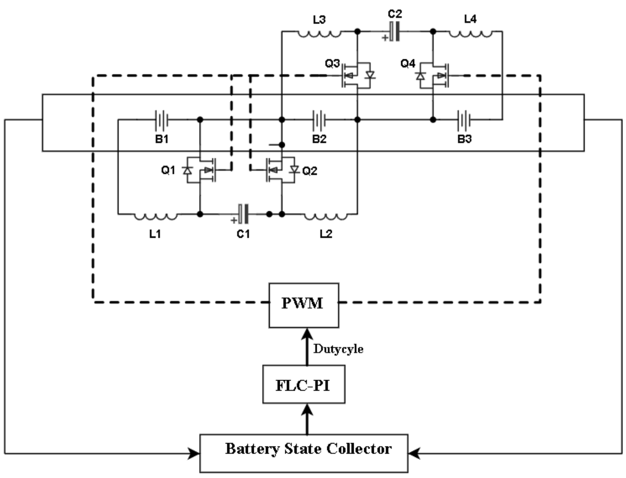


Fig. 1. Cuk circuit equalization with FLC-PI Control.

The Cuk converter is a type of DC-DC converter that has an inverse output voltage characteristic. The architecture of this circuit is divided into 2 parts as shown in Fig. 2 is equalizer 1, a equalizing circuit between cells *B1-B2* and equalizer 2, a equalizing circuit between *B2-B3*. Each pair of adjacent cells uses one equalizing circuit, which allows energy transfer between cells to achieve SOC balance in the entire battery pack[2][13].

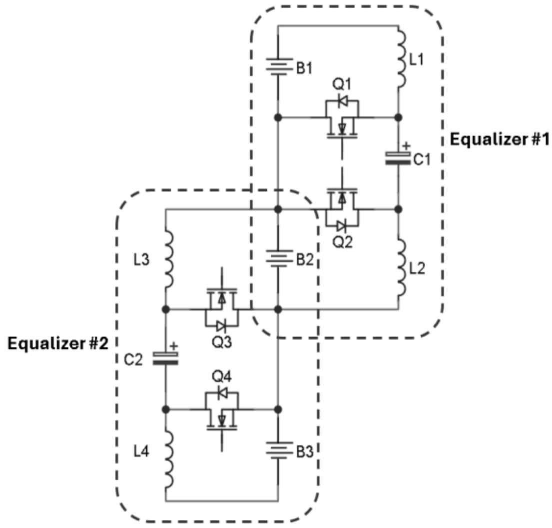


Fig. 2. Cuk circuit equalization.

B. Analysis of circuit working conditions.

The operation principle of energy transfer using a Cuk converter circuit, illustrated in Fig. 3 and Fig. 4, demonstrates a scenario wherein battery *B1* possesses a higher capacity compared to battery *B2* (*SOC_B1* > *SOC_B2*). Then, in this condition, *B1* transfers surplus energy to *B2*. Initially, no current flows through the converter, implying *Iec1* = *Iec2* = *0*, and MOSFET *Q1* is activated. In this state, battery *B1* discharges its stored energy into inductor *L1*, so as charging *L1*, while the intermediate capacitor C discharges energy to battery cell *B2* and inductor *L2*, causing *L2* to store energy. In the subsequent state, MOSFET *Q1* is switched off, forcing diode *D2* into active mode. Battery *B1* then flows its energy to inductor *L1* and capacitor C1. Simultaneously, the energy previously stored in inductor *L1* will flow to battery *B2*. This cycle continues until the electric current drops to zero, indicating that the converter has returned to its initial condition[14].

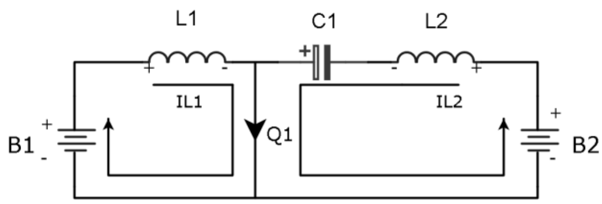


Fig. 3. Circuit diagram when MOSFET *Q1* is ON.

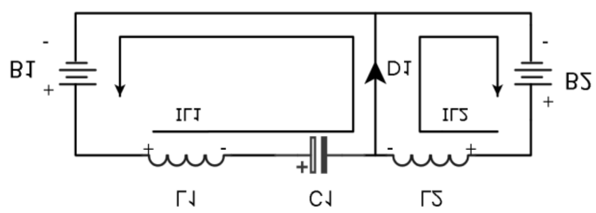


Fig. 4. Circuit diagram when MOSFET *Q1* is OFF.

When the SOC *B1* is higher than the battery SOC *B2* , then *Q1* turns on $(t0 < t < t1)$ and the equivalent equation can be written as follows[14] :

$$V_{B1} = L1\frac{di_{L1}}{dt} \tag{1}$$

$$V_{B2} = -L2\frac{di_{L2}}{dt} + \frac{1}{C}\int I_{L2}\,dt \tag{2}$$

$$V_{C1}(t0) = V_{B1} + V_{B2} \tag{3}$$

When *Q1* is switched off and *D2* is forced on $(t1 \leq t < t2)$, then the equivalent equation can be written as follows [14]:

$$V_{B1} = L2\frac{di_{L1}}{dt} + \frac{1}{C}\int I_{L2}\,dt \tag{4}$$

$$V_{C1}(t1) = V_{B1} + V_{B2} \tag{5}$$

$$V_{B2} = -L1\frac{di_{L2}}{dt} \tag{6}$$

In steady state, the average voltage across an inductor over one switching cyle must be zero can be written as follows[14]:

$$I_{L1}(1-D)Ts - I_{L2}DTs = 0 \tag{7}$$

When the current reaches a state of zero, the converter will return to its initial state. Based on this condition, inductor current (I_L) or balancing current is intended in this research (*Iec*) in cells *B1* and *B2* can be determination as follows[15]:

$$I_{L1} = [\frac{1}{2}(\frac{V_{cell1}}{L1}D^2 + \frac{-V_{c1}+V_{cell1}}{L1}(1-D^2))]Ts \tag{8}$$

$$I_{L2} = [\frac{1}{2}(\frac{-V_{c1}+V_{cell2}}{L2}D^2 + \frac{-V_{cell2}}{L2}(1-D^2))]Ts \tag{9}$$

C. Equalization Strategy

This section describes the working principle of the proposed battery equalizing system from start to end or balanced battery. Fig.5 shows the flowchat of the system working principle starting from the Battery state collector reading the SOC on each battery cell. Then from the collected parameters, the average battery SOC (*SOC_AVR*) and SOC difference (*SOC_DIF*) of adjacent battery are calculated. Then check the *SOC_DIF* is greater than the SOC difference setting (*SOCset*). If the SOC difference value does not exceed the *SOCset* value, the process is end. Conversely, if it exceeds the *SOCset* value, the process continues on Fuzzy Logic control to produce a equalizing current output as a equalizing reference current (Ie_{ref}). The output of the equalizing current is then processed by the Propotional Integral (PI) controller which aims to generate a dutycyle used to regulate the PWM of the Mosfet work system which works as a switch to control equalizing current. Then, if the battery is balanced the equalizing process will be completed, otherwise the process returns to the Fuzzy logic control process to determine the equalizing current and continue to the next step.

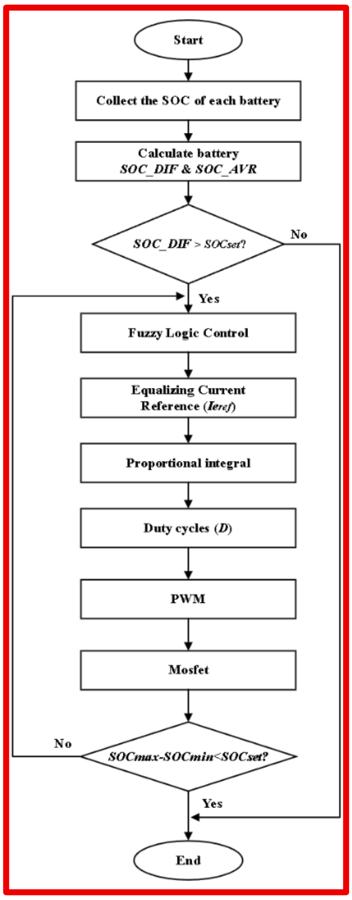


Fig. 5. Cuk circuit equalization scheme.

The control system used in this study accepts two main parameters as input that the SOC difference between cells and the average SOC value. Based on these two parameters, the design rules for the equalizing scheme are formulated as follows[3]:

- If the SOC difference and the average SOC are both large, then a high equalizing current is required to accelerate the equalizing process.
- If the SOC difference is large but the average SOC is low, then the equalizing current must be low to prevent potential damage to the battery.
- If the SOC difference is small but the average SOC is high, then a lower equalizing current is used to reduce energy loss.
- If both the SOC difference and the average SOC are small, then a minimum equalizing current is applied to avoid battery cell degradation.

The values of the SOC difference *SOC_DIF* and SOC average *SOC_AVR*, between two adjacent batteries can be expressed as follows:

$$SOC\_AVR = \frac{1}{2}(SOC_i + SOC_{i+1}) \tag{10}$$

$$SOC\_DIF = SOC_i - SOC_{i+1} \tag{11}$$

D. *Fuzzy Logic Control - PI*

The FLC modeling for the proposed control strategy has two inputs and one output are the average SOC, the difference between adjacent battery cells, and the equalizing current as the output. The domain of the average SOC (*SOC_AVR*) is (0-100), where this value corresponds to the battery percentage. Meanwhile, the domain of the SOC difference (*SOC_DIF*) is {0-10}; this parameter is based on experimental settings, as the maximum allowable imbalance is limited to 10%. The desired output range for the equalizing current is (0-1.3), where this parameter follows the charging current limits specified in the battery datasheet. The membership function consists of five variables: Very Small (*VS*), Small (*S*), Medium (*M*), Big (*B*), and Very B (*VB*). These variables are represented by triangular functions, as illustrated in Fig. 6 and 7.

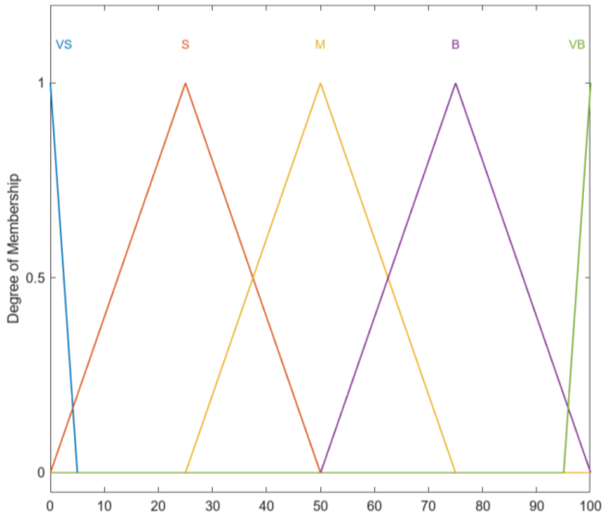


Fig. 6. Average SOC Input Variable *(SOC_AVR)*

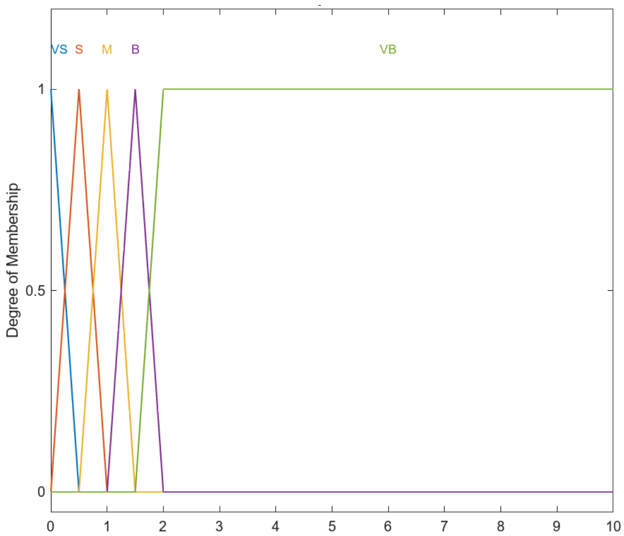


Fig. 7. Difference SOC Input Variable *(SOC_DIF)*

The FLC controller has one output that will be used as the battery equalizing current *(Iec)* and will then be processed as the input of the PI setting to be converted into a duty cycle to regulate the switching on the MOSFET. The membership function used has five linguistic variables that Very Small *(VS)*, Small *(S)*, Medium *(M)*, Big *(B)*, and Very Big *(VB)*, which are triangular in shape as shown in Fig. 8. Fuzzy rules use the statement rule 'IF A AND B THEN C' to form an algorithm that describes the control process. Fuzzy rules are shown in Table 1.

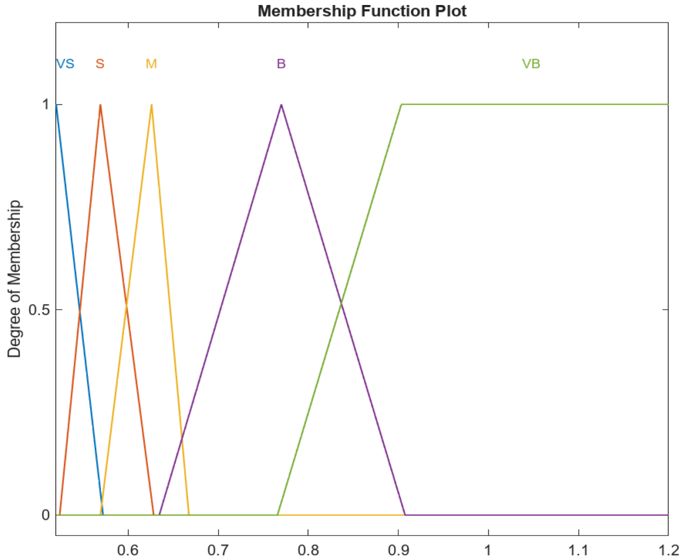


Fig. 8. Equalizing Current Output Variable *(Iec_{ref})*

TABLE I. RULE BASE FUZZY LOGIC

SOC_AVR/ SOC DIF	***VS***	***S***	***M***	***B***	***VB***
VS	VS	S	S	S	VS
S	VS	M	M	M	VS
M	S	M	M	M	S
B	S	M	B	B	S
VB	M	VB	VB	VB	M

Based on the basic rules of fuzzy logic control, the input–output mapping of the fuzzy controller is visualized in Fig. 9, which shows the relationship graph between input variables and equalizing current values. The magnitude of the equalizing current is determined from the difference map between *SOC_DIF* (SOC difference) and *SOC_AVR* (average SOC). When the SOC difference between adjacent cells and the average SOC increase, the equalizing current output will also increase. Conversely, if the SOC difference or average SOC decreases, the equalizing current is reduced to avoid damage to the cells in the series battery pack.

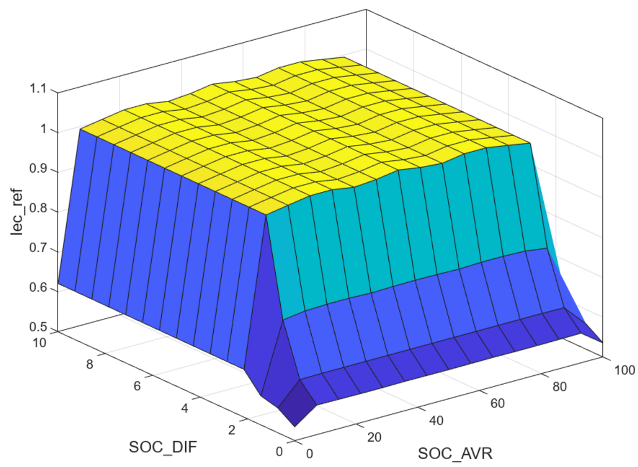


Fig. 9. Input-output mapping of fuzzy controller

In the operation principle of the equalizing current regulation discussed in this study, the Proportional-Integral Controller is combined with the Fuzzy Control to regulate the PWM switching of the MOSFET. This control is achieved by adjusting the equalizing current output generated by the Fuzzy Logic Controller (FLC) into a duty cycle value through time ratio modulation of the MOSFET's on-off signal. Table II presents the equalizing circuit parameters used in the simulation. Fig. 9 illustrates the block diagram of the Proportional-Integral Controller, where the control algorithm is based on the error value determined by the following equation:

$$Iec = Ie_{ref} - Ie_{measurement} \quad (12)$$

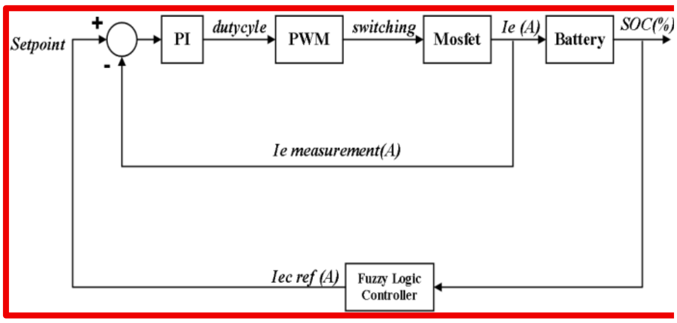


Fig. 10. PI Control Block Diagram

The control signal generated by this PI controller is expressed as follows:

$$u(t) = Kp.e(t) + K_I \int_0^t e(t)dt \quad (13)$$

TABLE II. PI CONTROLLER PARAMETERS

Parameters	***Values***
Proportional (P)	0.5
Integral (I)	10

III. RESULTS AND DISCUSSION

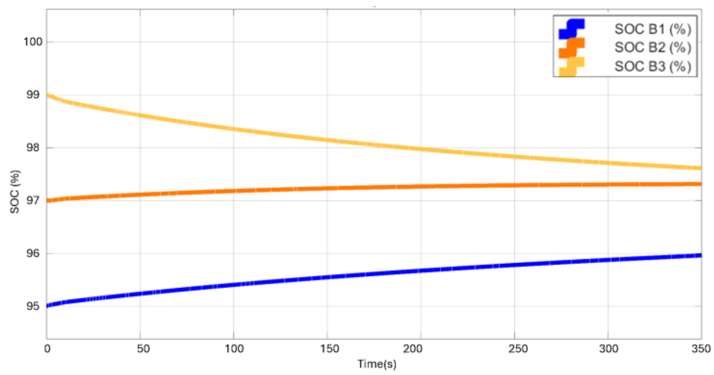
In this study, MATLAB/Simulink 2024a software was utilized to model and simulate the proposed battery equalizing technique. The battery model used is of the lithium-ion type, with the equalizer specifications shown in Table III. The proposed method is then compared with conventional methods with test scenarios including two cases is static testing, when the battery is in a stationary state, and dynamic testing, when the battery undergoes a charging-discharging with a constant current. For the equalizing scenario, it is assumed that the SOC imbalance between the batteries is 2%, with SOC values of 95% (B_1), 97% (B_2), and 99% (B_3) The duration for each equalizing test scenario is set to 350s due to limitations in the computer's ability to run the simulation software.

TABLE III. PARAMETERS OF THE EQUALIZER

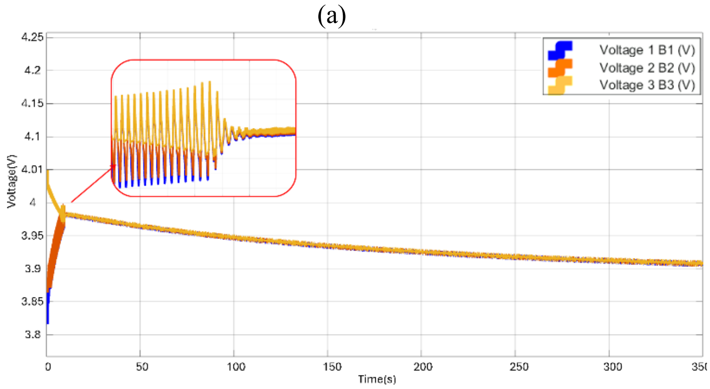
Parameters	***Value***
Battery Type	NCR18650
Single-cell voltage	4.2 V
Max charge current	1.3 A
switching Frequency	20 kHz
inductance	756.57mH
capacitance	38.535 uF

A. Idle Condition Case

The performance comparison of battery equalizing from static testing between the conventional technique and the proposed algorithm is shown in Fig. 11 and 12. It is seen that the proposed technique provides better equalizing performance compared to the conventional technique, which uses voltage as the control variable. In the conventional technique, during the 350s simulation test, it was able to balance the voltage of the three batteries in 9 seconds at a voltage of 3.97V. However, as seen in Fig. 11a, this equalizing did not fully resolve the SOC differences of the three battery cells. After the voltage of the three cells was balanced, the SOC of *B1* was 95.07%, *B2* was 97.03%, and *B3* was 98.88%. Next, turning to Fig. 11c, it can be seen that the equalizing current of both equalizers oscillates high when the voltage starts to stabilize, which indicates that the conventional equalizing technique with voltage as the control variable provides a fast response to voltage changes but does not fully address the SOC differences of the three cells.



(a)



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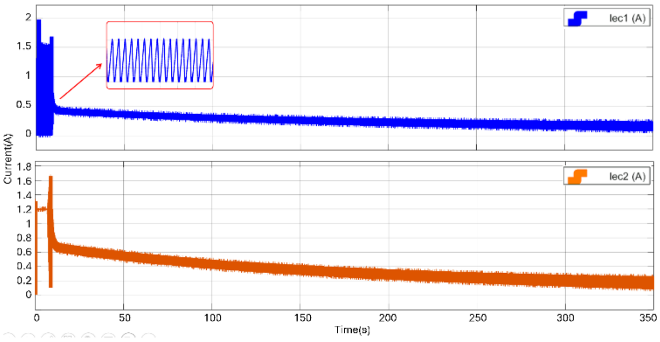
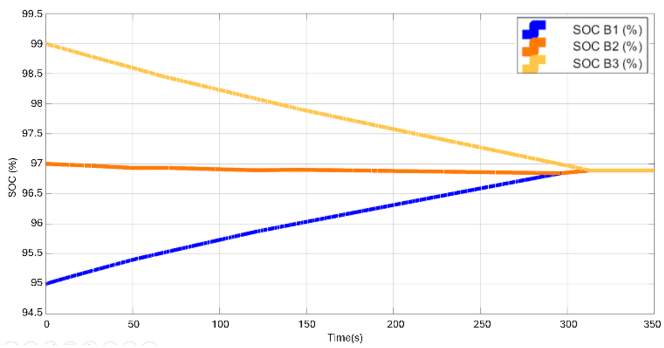


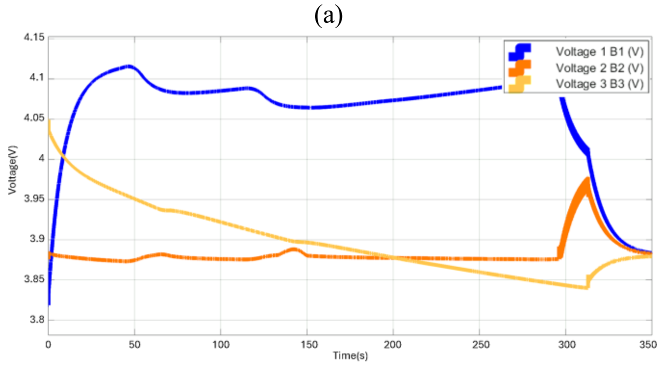
(c)

Fig. 11. Equalizing results with conventional method for $SOC_{B1} < SOC_{B2} < SOC_{B3}$. (a) SOC Response. (b) Voltage Response. (c) Current equalizing(*Iec*) *B2* to *B1* & *B3* to *B2*.

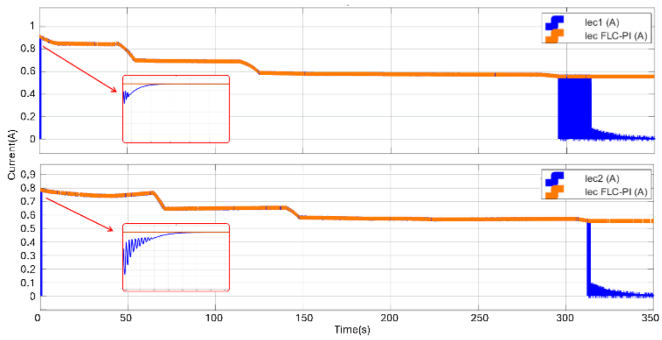
In the proposed equalizing technique using FLC-PI and SOC as the control variable, this technique is able to balance the three batteries in 337s at a voltage of 3.87V. Unlike the conventional equalizing technique, the proposed technique effectively addresses the SOC differences across the three battery cells. The voltage response is shown in Fig. 12b, where the equalizing using the proposed technique exhibits a different voltage response compared to the conventional technique. It can be seen that the battery cell with the lowest SOC tends to have a higher voltage compared to other cells, due to the charging process caused by energy transfer from adjacent cells. Additionally, as seen in Fig. 12c, the proposed technique provides a equalizing current response that dynamically decreases gradually as the SOC gap of the two batteries decreases following the reference current generated by the FLC controller. The simulation results demonstrate that the proposed technique resolves the issues encountered in conventional equalizing techniques, effectively completing the overall equalizing process of the three cells.



(a)



(b)

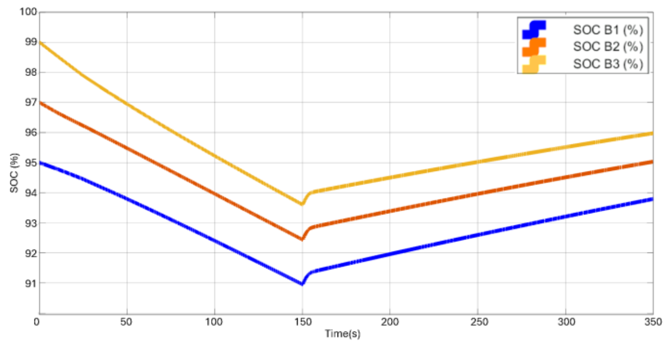


(c)

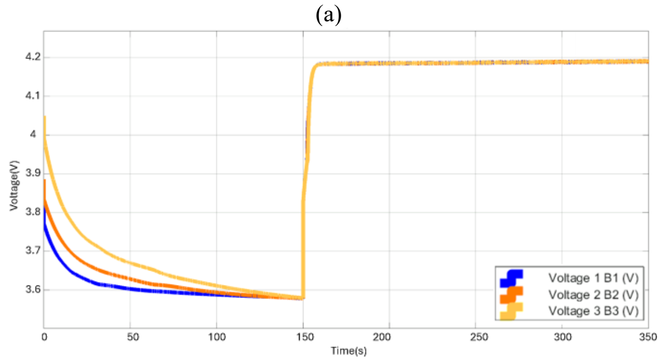
Fig. 12. Equalizing results of proposed topology for $SOC_{B1}<SOC_{B2}<SOC_{B3}$. (a) SOC Response. (b) Voltage Response. (c) Current equalizing(*Iec*) *B2* to *B1* & *B3* to *B2*.

B. Charge and discharge Condition Case

The performance comparison of battery equalizing from dynamic testing with constant current charge-discharge cycles between the conventional technique and the proposed technique is shown in Fig. 13 and 14. The simulation test scenario remains the same, conducted over 350s seconds. During the first 150 seconds, the battery is discharged, followed by charging in the subsequent seconds. Simulation results show that the proposed technique provides better equalizing performance compared to the conventional technique. The conventional technique is only able to balance the voltage of the three batteries in 24.4s at a voltage of 3.65V. However, as shown in Fig. 13a, this equalizing still does not fully resolve the SOC differences among the three battery cells. After the voltage of the three cells is balanced, the SOC values are as follows: *B1* at 94.4%, *B2* at 96.2%, and *B3* at 97.9%. Then to Fig. 13c, it can be seen equalizing current response from both equalizers exhibits higher oscillations compared to when the battery is in an idle state. This demonstrates that the conventional equalizing technique, which uses voltage as the control variable, results in a rapid voltage response. However, it still does not fully resolve the SOC differences among the three cells.



(a)



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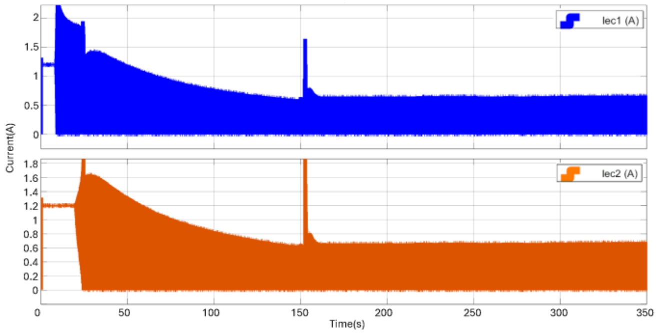
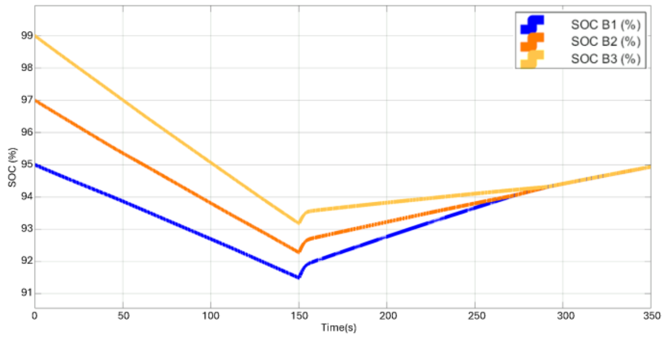


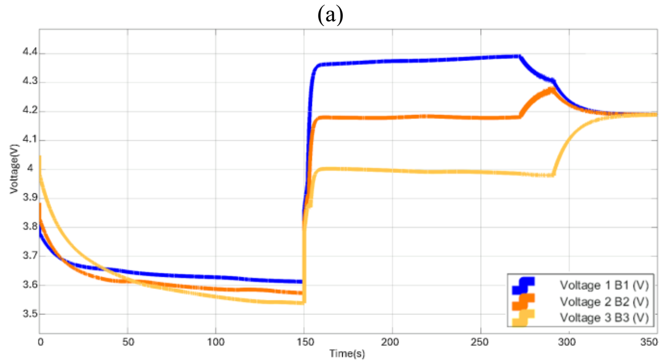
(c)

Fig. 13. Equalizing results with conventional method for $SOC_{B1} < SOC_{B2} < SOC_{B3}$. (a) SOC Response. (b) Voltage Response. (c) Current equalizing(*Iec*) *B2* to *B1* & *B3* to *B2*.

In the proposed equalizing technique using FLC-PI with SOC as the control variable, this technique can balance the three batteries in 289 seconds and achieve equilibrium at a SOC condition of 94.2%. The voltage response is shown in Fig. 14b, where the equalizing using the proposed technique still exhibits a different response compared to the conventional technique. It can be seen that the battery cell that has the lowest SOC tends to have a higher voltage compared to the other cells, due to the charging process induced by energy transfer from the adjacent cells. Additionally, as seen in Fig. 14c, the proposed technique demonstrates performance with a equalizing current response similar to that of the static test condition. The proposed technique provides a equalizing current response that dynamically decreases gradually as the SOC gap of the two batteries decreases, following the reference current generated by the FLC controller. The simulation results indicate that the proposed technique successfully resolves the issues encountered in conventional equalizing techniques, and the equalizing current response remains unaffected by the charging or discharging conditions, resulting in an optimal equalizing current transfer.



(a)



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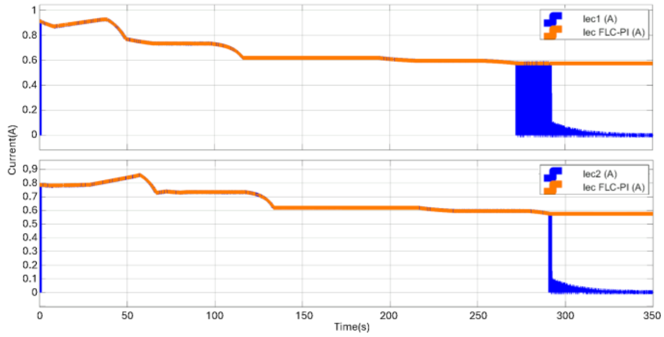

(c)

Fig. 14. Equalizing results of the proposed topology for $SOC_{B1}<SOC_{B2}<SOC_{B3}$. (a) SOC Response. (b) Voltage Response. (c) Current equalizing(*Iec*) *B2* to *B1* & *B3* to *B2*.

IV. Conclusion

This study proposes an active battery equalizing scheme based on an adjacent cell-to-cell (A-C2C) architecture using an FLC-PI controller with State of Charge (SOC) as the control variable. The performance of the proposed topology and algorithm is tested and evaluated through comparative simulations against conventional techniques that still use voltage as the control variable, by testing in two scenarios of static (idle) and dynamic (discharging-charging) conditions. The simulation results show the proposed equalizing technique has better performance when compared to conventional techniques. In both test scenarios, this technique successfully overcomes various limitations found in conventional equalizing techniques. Overall, the equalizing technique proposed in this study is able to significantly improve the efficiency of equalizing time while maintaining all battery cells in safe operating conditions through a equalizing current control mechanism that dynamically follows battery conditions. In the idle condition, the proposed FLC-PI algorithm reaches the balanced point in 300 seconds and in the discharging-charging condition, it takes 289 seconds. While, the conventional method, during the simulation period of 0-350 seconds, has not yet reached the balanced point.

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