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Fuzzy Equalization Strategy Based on Multilayer Circuits

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Authors' contributions

This work was carried out in collaboration between both authors. Authors XL and CW conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—review and editing, visualization, supervision, project administration of the manuscript. Both authors have read and agreed to the published version of the manuscript.

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ABSTRACT

In this study, the influence of the external current and the equalization current on the working current of the lithium battery during the equalization process is fully analyzed, a fuzzy equalization approach based on a multilayer circuit is proposed, with external current and the battery's SOC as inputs, and fuzzy rules to output a suitable equalization current to keep the battery's operating current within the permitted range. It is verified by simulation that the proposed fuzzy control strategy can limit the operating current of the lithium battery within the range of [-3A-3A], and the maximum operating current of the battery is reduced by 50% compared with the unbalanced strategy. It can ensure the safety in the process of battery balancing.

Keywords: Battery active equalization; fuzzy control; equilibrium strategy; multilevel equilibrium.

1. INTRODUCTION

With environmental pollution and energy scarcity, all governments have implemented a variety of policy measures to address the issue. Lithium batteries are utilized on a large scale in many energy storage systems due to their high energy density, long life, good consistency, and other advantages [1-5]. However, because the voltage of a single lithium battery is typically 3V-4.2V [6],

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and the maximum capacity is only a few AH or tens of AH, lithium batteries must be combined in series and parallel to form battery packs to meet the needs of everyday use [7]. However, because of the impact of materials, production techniques, and other factors on each battery manufacture, the cells within the battery pack will frequently display inconsistent phenomenon [8]. With the use of the battery and the influence of the external environment, the rated capacity and other parameters of the battery will gradually change, exacerbating the battery's inconsistency. Short-term inconsistencies may result in a reduction in the battery pack's rated capacity, and when inconsistencies occur over time, the internal structure of some batteries is damaged, and the battery pack's capacity is greatly reduced, potentially causing damage to the battery and, in extreme cases, posing a safety hazard. For example, in 2019, firefighters were seriously injured in an accident at an energy storage plant in Arizona, USA; in 2021, two firefighters were seriously injured in a fire at the Fengtai energy storage plant in Beijing; and in South Korea, more than 30 energy storage accidents occurred between 2018 and 2020.

When many single cells are coupled in series and parallel to form a battery pack, the charge and discharge currents of the series-connected cells are the same [9]. When one of the lithium batteries in the pack is fully charged or discharged, it is required to disconnect the battery pack from the external power supply or load to prevent overcharging and over-discharging. As a result, the battery pack will not be fully charged and discharged, limiting the battery pack's actual usage time [10, 11]. Equalizing and controlling the battery pack is important to enhance the consistency of the batteries within the pack, raise the real capacity of the battery pack, and extend the battery pack's life.

The equalization circuit is the equalization system's hardware guarantee and the foundation for increasing equalization efficiency and decreasing equalization time. Active equalization and passive equalization are the two main equalization approaches currently in use [12, 13]. The energy dissipation device in passive equalization is primarily a resistor, and the low SOC cells in the group are used as a benchmark to discharge the high SOC cells in the group until it reaches equilibrium. The advantages of the passive equalization method are simple construction, minimal cost, and a straightforward equalization process. Passive equalization, on the other hand, loses energy in the form of work, resulting in a significant loss of energy as well as an increase in heat in the battery pack, which can cause substantial safety hazards in extreme circumstances. Active equalization allows charge to flow between different energy storage devices, transferring power from a high SOC battery to a low SOC battery and achieving an energy transfer. Active equalization, as opposed to passive equalization, decreases energy losses, improves energy equalization efficiency, and maximizes the battery's usable capacity.

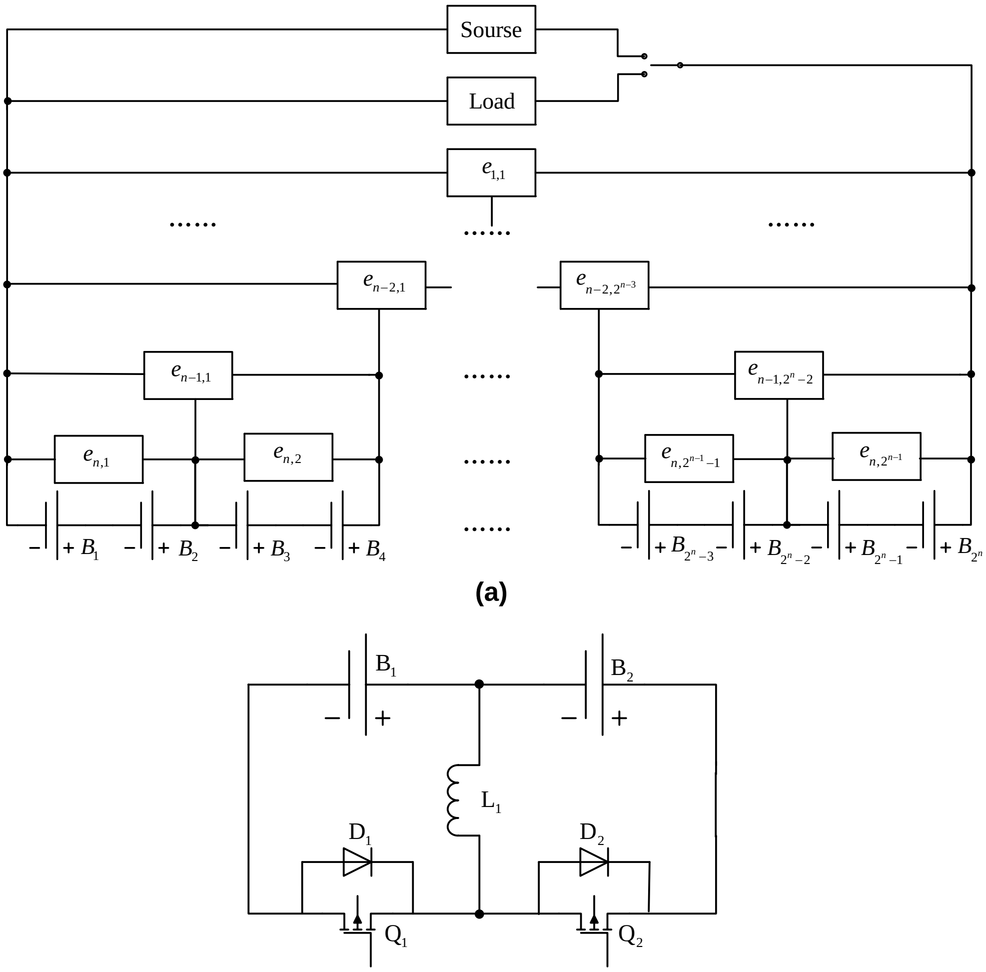
Active equalization circuits can be separated into capacitive equalization circuits, transformer equalization circuits, and inductive equalization circuits depending on the energy storage element. Reference [14] provides an inductive equalization circuit with an arbitrary number of inductors that uses less than half the number of inductors in the battery, lowering the cost while ensuring the battery pack's equalization effect. Reference [15] provides a bidirectional flyback converter-based battery pack equalization circuit that uses the battery's remaining power as the equalization indicator and the flyback converter as the energy transfer device, decreasing the number of components and the equalization unit's size. A series battery pack equalization circuit with many layers that work simultaneously and do not affect each other during equalization is proposed in reference [16], speeding up the equalization process. For various equalization circuits, numerous equalization strategies have been presented. The battery SOC and voltage were used as equalization variables in reference [17], which presented an equalization approach based on fuzzy control and inverted neural networks. To shorten the equalization time, the inverse neural network is used to estimate the battery SOC, and fuzzy control is used to estimate the equalization current. However, the equalization is likely to create excessive battery operating current and degrade the battery life. The literature[18] proposes a control strategy based on a two-layer equalization circuit that uses a particle filtering algorithm to calculate the battery's SOC and realizes the design and optimization of the equalization strategy based on the difference in SOC between batteries to achieve the adjustment of the equalization current, which improves equalization speed but still exceeds the allowed value. Reference [19] proposed a fuzzy control-based equalization algorithm that uses the battery SOC as the equalization variable and improves equalization efficiency by 23% over the mean difference algorithm. However, the method does not account for the influence of the external current on the battery, and the battery's operating current will still exceed the limit.

In conclusion, while the above equalization circuits and equalization approaches have improved results, there are still certain flaws. Faster equalization circuits have larger equalization currents and will shorten battery life, but slower equalization circuits are inefficient and have no effect on the battery's real capacity. In this study, a fuzzy equalization approach is developed using a multi-layer equalization circuit that takes the external current and the battery pack's SOC as inputs and outputs the appropriate equalization current after fuzzy operations to ensure that the battery functions within normal bounds. Not only can the multi-layer equalization circuit's quick equalization speed be taken advantage of, but the battery's safety can also be ensured.

2. ACTIVE EQUALIZATION CIRCUIT TOPOLOGY AND OPERATING PRINCIPLE

2.1 Circuit Structure

Fig. 1 depicts the multilayer equalization circuit used in this paper. The overall structure is shown in Fig. 1a, and the buck-boost circuit schematic is shown in Fig. 1b. The equalization circuit as a whole has n layers, and each of those layers controls 2^n individual cells. Each equalizer in the nth layer equalizes two single cells, the n-1st layer equalizer equalizes four neighboring single cells, and so on, with the nth layer equalizer capable of equalizing the complete battery pack. Fig. 1b shows the buck-boost circuit schematic, which consists of two MOSFET switches and an energy storage inductor.



(a)

(b)

Fig. 1. (a) Battery equalization structure diagram; (b) Schematic of the equalization

2.2 Principle of Operation

A four-battery double-layer equalization circuit is given briefly to illustrate the multilayer circuit's working concept. Fig. 2 depicts the equalization circuit structure. This paper will focus on the effect of external current on the battery current while charging and discharging because the equalization process is relatively straightforward when the battery is at rest.

2.2.1 Charging equalization

Assume that the SOC of battery B1 is greater than that of battery B2, that the SOC of battery B3 is more than that of battery B4, and that the SOC of batteries B1 and B2 is greater than that of batteries B3 and B4. The following equation can be used to express equalization on conditions:

$$\begin{aligned}&SOC_{B1}-SOC_{B2}>SOC_T\\&SOC_{B3}-SOC_{B4}>SOC_T\\&\frac{SOC_{B1}+SOC_{B2}}{2}-\frac{SOC_{B3}+SOC_{B4}}{2}>SOC_T\end{aligned}\tag{1}$$

T denotes the MOSFET switch's period, D represents the duty cycle, and t is the operating duration within a cycle. The process of equalization can be separated into two steps.

(1) First stage: as indicated in Fig. 3a, 0<t<DT, high SOC battery discharge. MOSFET switches Q1 and Q3 open at this time, forming a circuit between the battery and the inductor. At this time, the first layer of the equalization circuit will open equalization, and battery B1 will transfer energy to inductor L1, while battery B3 will transfer energy to inductor L2; MOSFET switch Q5 will open, and battery B1, B2, and inductor L3 will form a circuit; and the second layer of the equalization circuit will open equalization, and battery B1 B2 will transfer energy to inductor L3. The MOSFET switch open and charging stops when t=DT, at which moment the inductor current reaches its maximum value.

The current flowing through the batteries B1, B2, B3, and B4 at this point can be represented as

$$\begin{aligned}&I_{B1}=I-I_{1,C}-I_{3,C}\\&I_{B2}=I-I_{3,C}\\&I_{B3}=I-I_{2,C}\\&I_{B4}=I\end{aligned}\tag{2}$$

I is the external charging current, $I_{1,C}$ is the equalization current flowing through inductor L1, $I_{3,C}$ is the equalization current flowing through inductor L3, and $I_{2,C}$ is the equalization current flowing through inductor L2.

(2) Fig. 3b shows the second stage: DT<t<T, low SOC battery charging. For the first level of the equalization circuit, battery B2 and inductor L1 form a circuit, and battery B4 and inductor L2 form a circuit. The energy stored in inductor L1 will be transferred to battery B2, and the energy stored in inductor L2 will be

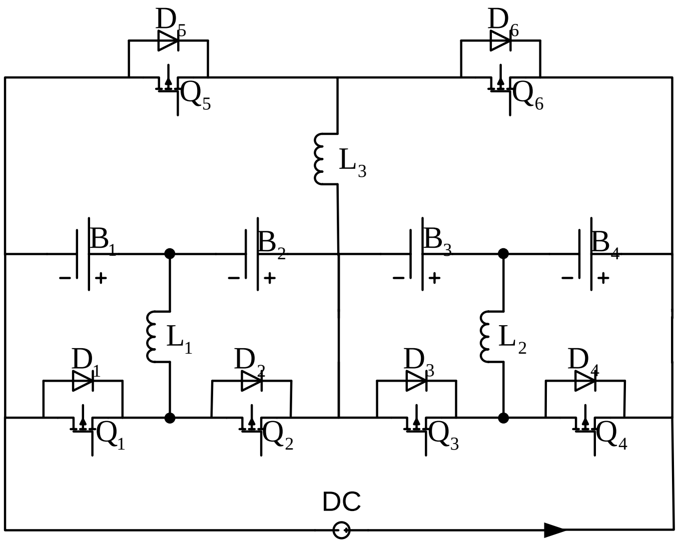


Fig. 2. Battery pack equalization circuit

transferred to battery B4; battery B3, B4, and inductor L3 form a circuit for the equalization circuit's second level, and the energy stored in inductor L3 will be transferred to battery B3, B4. It comes to a halt when the current in the inductor reaches zero.

At this moment, the current flowing through batteries B1, B2, B3, and B4 can be expressed as follows:

$$\begin{aligned} I_{B1} &= I \\ I_{B2} &= I + I_{1,D} \\ I_{B3} &= I + I_{3,D} \\ I_{B4} &= I + I_{2,D} + I_{3,D} \end{aligned} \tag{3}$$

Where I_{B1} is the current flowing through battery B1, I_{B2} is the current flowing through battery B2, I_{B3} is the current flowing through battery B3, I_{B4} is the current flowing through battery B4, I is the external charging current, and $I_{1,D}$ is the equalization current flowing through inductor L1, $I_{3,D}$ is the equalization current flowing through inductor L3, and $I_{2,D}$ is the equalization current flowing through inductor L2.

2.2.2 Discharge equalization process

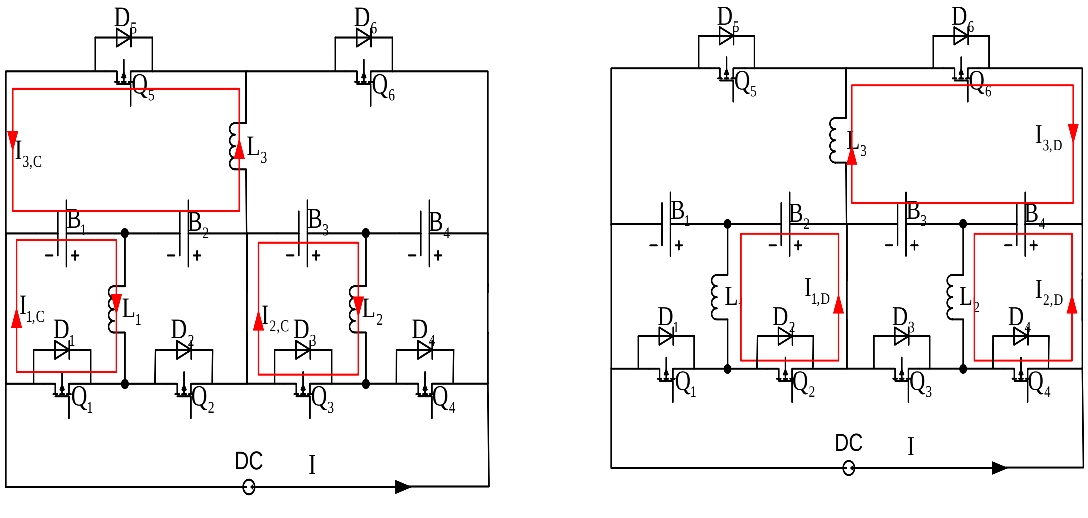
The SOC of battery B2 is assumed to be higher than the SOC of battery B1, the SOC of battery B4 is assumed to be higher than the SOC of battery B3, and the SOC of batteries B1 and B2 is assumed to be greater than the SOC of batteries B3 and B4. The following equation can be used to express the equalization turn-on condition:

$$\begin{aligned} & SOC_{B2} - SOC_{B1} > SOC_T \\ & SOC_{B4} - SOC_{B3} > SOC_T \\ & \frac{SOC_{B1}+SOC_{B2}}{2} - \frac{SOC_{B3}+SOC_{B4}}{2} > SOC_T \end{aligned} \tag{4}$$

T denotes the MOSFET switch's period, D represents the duty cycle, and t is the operating duration within a cycle. The process of equalization can be separated into two steps.

(1) Phase 1: As illustrated in Fig. 4a, 0<t<DT, high SOC battery discharge. MOSFET switches Q2 and Q4 open at this point, forming a circuit between the battery and the inductor. When the first layer of the equalization circuit opens equalization, battery B2 will transfer energy to inductor L1, battery B4 will transfer energy to inductor L2; MOSFET switch Q5 opens, battery B1 B2 and inductor L3 form a circuit, when the second layer of equalization circuit opens equalization, battery B1 B2 will transfer energy to inductor L3, when t = DT, MOSFET switch off, charging stops, the current in the inductor reaches a maximum value.

The current flowing through the batteries B1, B2, B3, and B4 at this time can be represented as



(a)

(b)

Fig. 3. (a) Schematic of first stage of charge equalization, (b) Schematic of the second stage of charge equalization

$$\begin{aligned} I_{B1} &= I - I_{3,C} \\ I_{B2} &= I - I_{1,C} - I_{3,C} \\ I_{B3} &= I \\ I_{B4} &= I - I_{2,C} \end{aligned} \tag{5}$$

I is the external charging current, $I_{1,C}$ is the equalization current flowing through inductor L1, $I_{3,C}$ is the equalization current flowing through inductor L3, and $I_{2,C}$ is the equalization current flowing through inductor L2.

(2) Fig. 3b shows the second stage: DT<t<T, low SOC battery charging. The first level of the equalization circuit is formed by battery B1 and inductor L1, while the second level is formed by battery B3 and inductor L2. The energy stored in inductor L1 will be transferred to battery B1, and the energy stored in inductor L2 will be transferred to battery B4; battery B3B4 and inductor L3 form a circuit for the equalization circuit's second level, and the energy stored in inductor L3 will be transferred to battery B3B4. It comes to a halt when the current in the inductor reaches zero.

At this moment, the current flowing through battery B1B2B3B4 can be expressed as follows:

$$\begin{aligned} I_{B1} &= I + I_{1,D} \\ I_{B2} &= I \\ I_{B3} &= I + I_{2,D} + I_{3,D} \\ I_{B4} &= I + I_{3,D} \end{aligned} \tag{6}$$

Where I_{B1} is the current flowing through battery B1, I_{B2} is the current flowing through battery B2, I_{B3} is the current flowing through battery B3, I_{B4} is the current flowing through battery B4, I is the external charging current, $I_{1,D}$ is the equalization current flowing through inductor L1, I3,D is the equalization current flowing through inductor L3 and I2,D is the equalization current flowing through inductor L2.

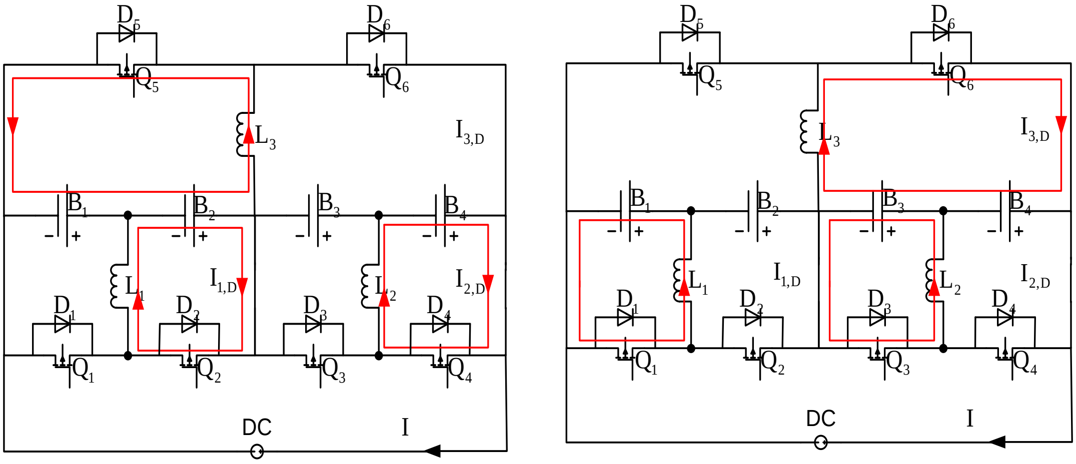
3. FUZZY CONTROL BASED EQUALIZATION STRATEGY

This research provides a fuzzy control-based equalization method to achieve safe and rapid equalization of the battery pack, which takes the external current and average SOC as input and the equalization current as output to ensure that the battery functions within the normal range.

When the average SOC difference between adjacent battery modules is more than the defined threshold, the equalization turn-on condition takes the SOC difference judgment.

$$\left| \frac{SOC_1 + SOC_2 + \cdots + SOC_K}{K} - \frac{SOC_{K+1} + SOC_{K+2} + \cdots + SOC_{2K}}{K} \right| > SOC_T \tag{7}$$

When the equalization on condition is reached at each layer, the equalization circuit is engaged. In this paper, the SOC threshold is fixed at 1%.



(a)

(b)

Fig. 4. (a) Schematic of first stage of discharge equalization, (b) Schematic of the second stage of discharge equalization

The equalization approach presented in this study employs fuzzy control to modify the equalization current, resulting in rapid and safe battery pack equalization. Fig. 5 depicts the fuzzy control logic, which includes a fuzzer, a rule base, an inference machine, and a fuzzified. The fuzzes the input external current and SOC values, which are then processed by the inference machine and fuzzy rule base, and the result is finally converted into an accurate output by the fuzzified.

3.1 Design of A Fuzzy Controller

The battery's maximum operational current is set to [-3A-3A] to guarantee safe operation. The SOC and external current are the fuzzy controller's inputs. It should be noticed that the external current of batteries B3 and B4 for the battery charging equalization operation is I+I3C, not I. The external current of each battery must be solved in the same way for more layers of equalization circuits. The input SOC and external current will be translated into two fuzzy values of u(x) and u(y), which will be separated into five fuzzy classes, very small (VS), small (S), medium (M), large (B), and very large (VB), with the external current ranging from [0-3A] and the SOC ranging from [0-100 percent]. Table 1 shows the empirically proven fuzzy control rules.

1) When the external current Iex is excessively high, a modest current should be provided for equalization to keep the battery from overheating.
2) Use a medium-size current to equalize when the battery SOC is too high and the external current Iex is too low to prevent the battery from overheating.
3) If the battery SOC is low and the external current Iex is low, use a medium size with you to keep the battery balanced and avoid overheating.
4) To increase equalization speed, the equalization current must be adjusted according to the magnitude of the external current if the battery SOC is medium.

The triangular affiliation function is used as the fuzzy control function in this paper. The fuzzy control toolbox in Matlab is used to view the relationship between the input and output to assess the accuracy of the defined fuzzy function. The developed fuzzy control's relationship diagram is illustrated in Fig. 5. The fuzzy controller will produce a bigger equalization current to increase the equalization speed when the external current I is small, and vice versa when the external current I is large. As a result, the fuzzy rules proposed in this study can be utilized to manage the equalization current and finish the equalization. The inference machine's output must be defuzzified because it is still a fuzzified variable. The center of gravity defuzzification method will be utilized in this work.

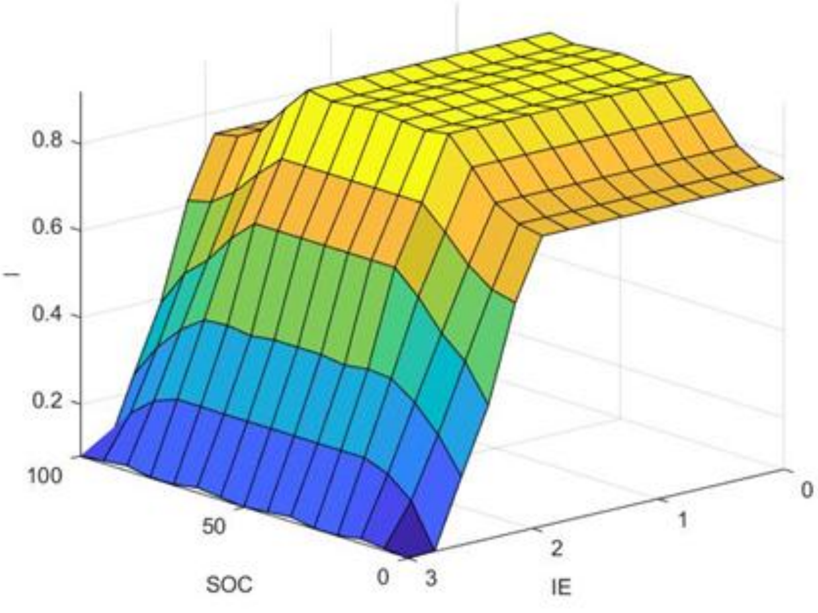


Fig. 5. input/output surface diagram

Table 1. Fuzzy rule table

I_{equ}		**SOC**				
		VS	**S**	**M**	**B**	**VB**
I_{ex}	VS	B	VB	VB	VB	B
	S	M	B	B	B	M
	M	S	M	M	M	S
	B	VS	S	S	S	VS
	VB	VS	VS	VS	VS	VS

4. SIMULATION RESULTS AND DISCUSSION

MATLAB can simulate real experiments in many cases, so this paper uses MATLAB to build an equalization circuit [17]. The rated capacity of the lithium battery is set to 0.2Ah to speed up the equalization, and the battery's initial SOC is illustrated in Fig. 6. Fig. 7 depicts the external loading current. The battery, MOSFET switch, inductor, and fuzzy control module are all included in the simulation model. The equalization current is regulated by the fuzzy control module, which adjusts the duty cycle of the PWM output based on the input SOC and external current output. The battery operating current is 0-3A, and the maximum equalizer current is 1A. The designed fuzzy control equalizer's performance will be tested further down.

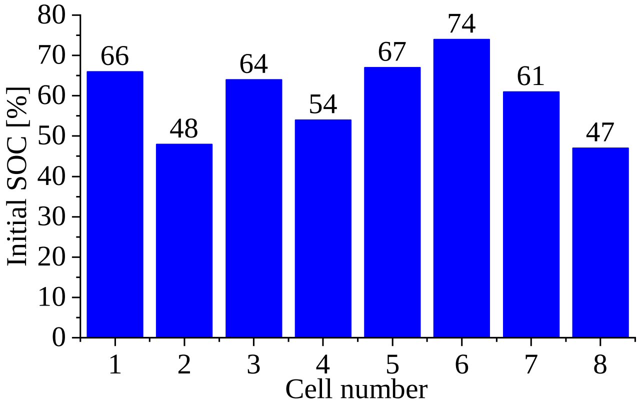


Fig. 6. Initial SOC

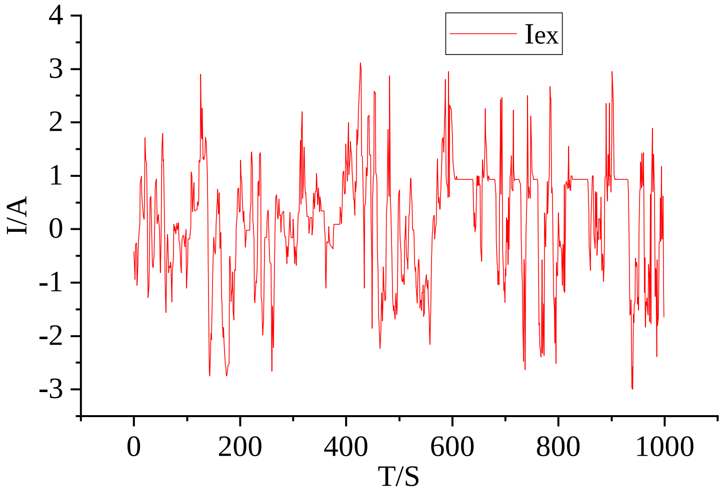


Fig. 7. External current

4.1 Performance Verification of Fuzzy Control Algorithms

A number of multi-layer circuit equalization techniques have been presented by academics. The multilayer equalization circuits will work simultaneously to improve equalization efficiency, which may result in excessive battery current and increased battery heat output in some instances. Figs. 8-9 illustrate the variation of the battery's SOC and current after simulation analysis. The simulation results reveal that the battery pack's SOC reaches equilibrium when the equalization time is 264.8s. The maximum battery current when operating at a high external current is 5.9A, which is significantly more than the regular operating current.

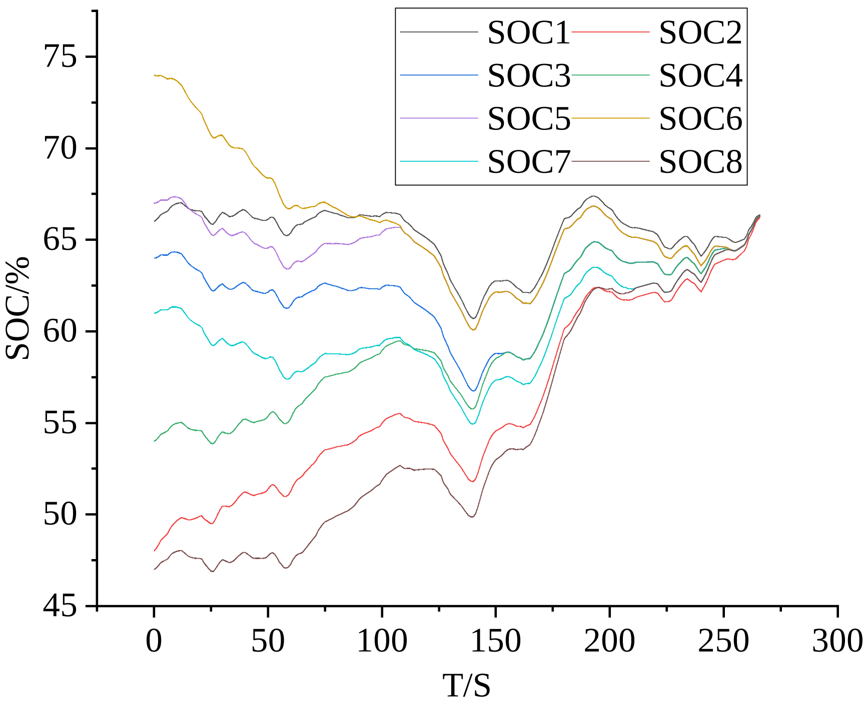
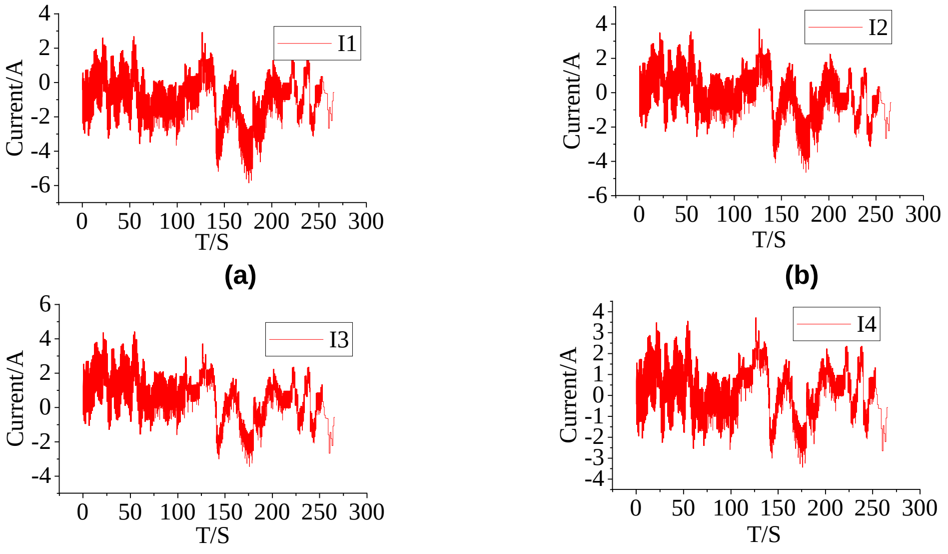


Fig. 8. Equilibrium process SOC changes

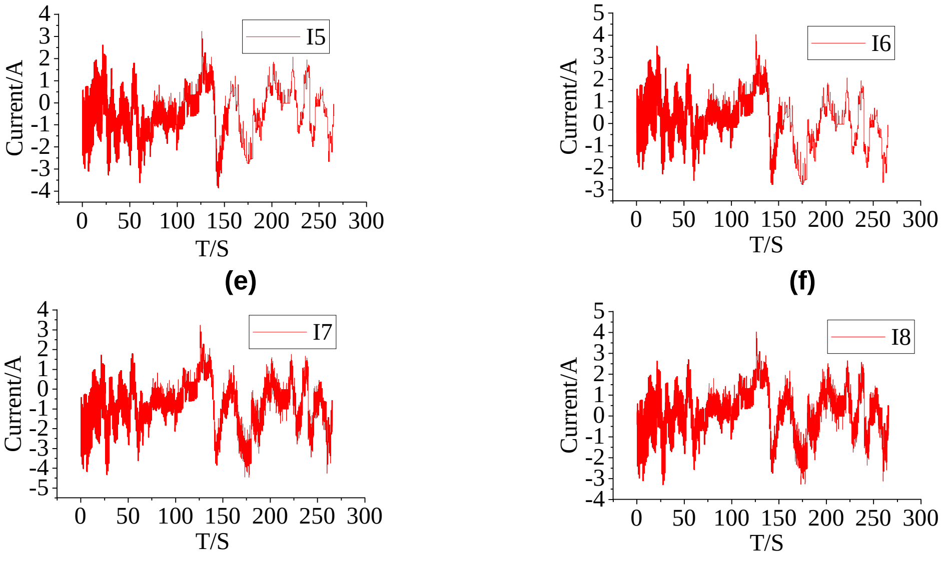


(a)

(b)

(c)

(d)



(e) (f)

(g) (h)

Fig. 9. Equalisation process current variation

Figs. 10-11 show the equalization results based on the fuzzy control method. When the equalization time is 376.4s, the battery is equalized, and the battery current is better maintained within the permissible range when running at greater external currents, as shown in the figure. This equalization method minimizes the operating current of the battery and makes the equalization procedure safer when compared to equalization results without the equalization strategy.

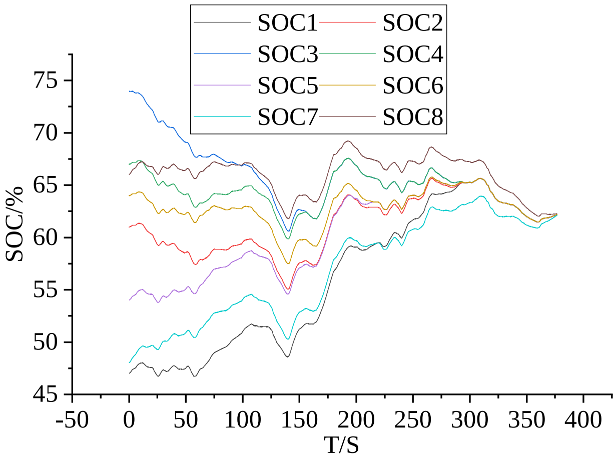
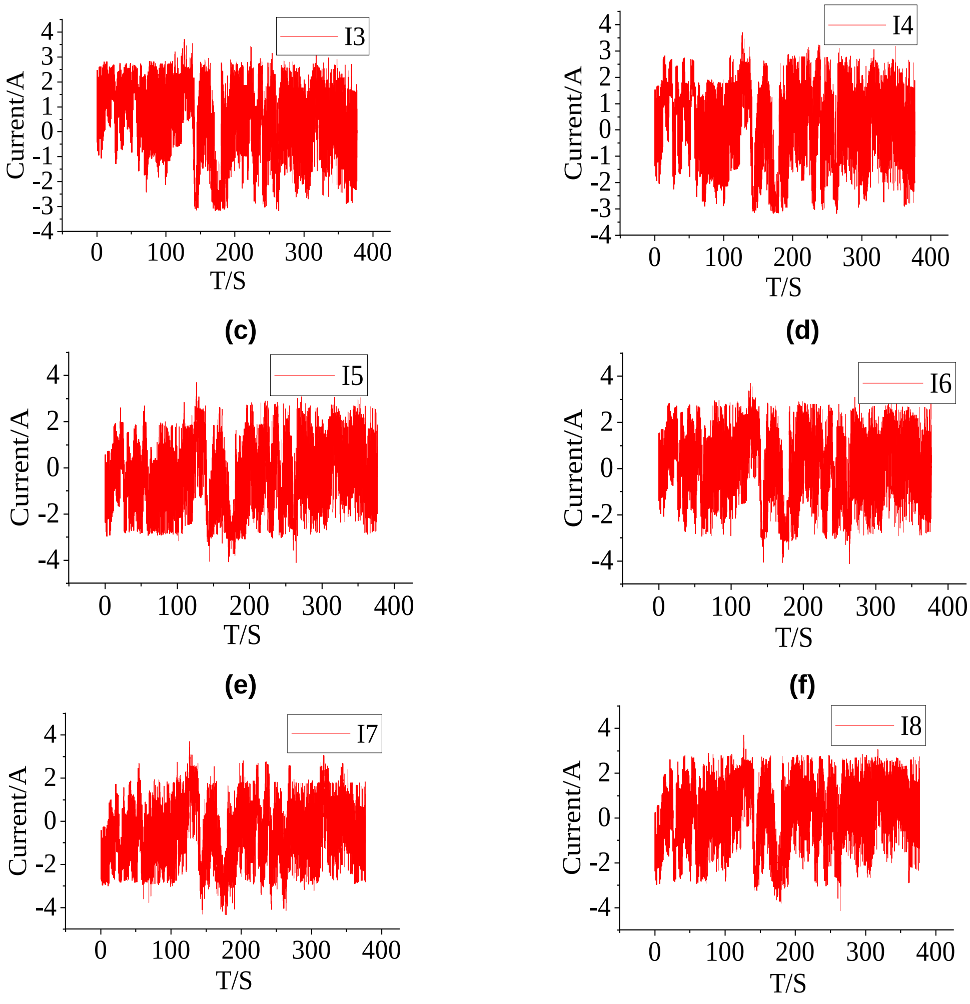


Fig. 10. Equilibrium process SOC changes

(a) (b)



(c) **(d)**

(e) **(f)**

(g) **(h)**

Fig. 11. Equalisation process current variation

4.2 Adaptability Testing

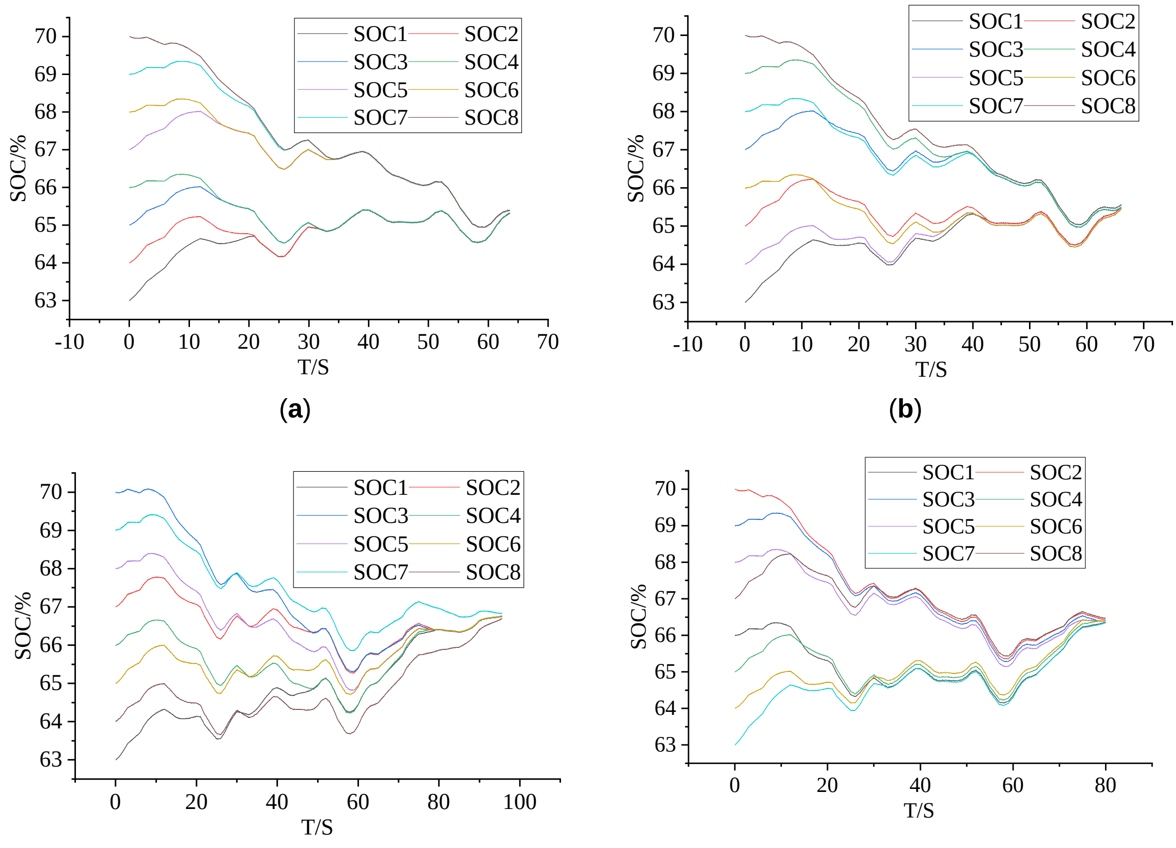
Finally, the battery pack will be tested for equalization with various beginning SOCs to verify the performance of the fuzzy control method. The current shown in Fig. 7 is the external loading current. The following are the initial SOCs:

- Case 1: SOC(0) = [66,48,64,54,67,74,61,47].
- Case 2: SOC(0) = [53,28,25,55,32,41,37,48].
- Case 3: SOC(0) = [25,29,32,36,42,47,52,55].
- Case 4: SOC(0) = [27,40,47,25,36,52,55,32].

Fig. 12 depicts the equalization results at these four starting SOCs. The simulation results show that the battery pack can be equalized in every situation, implying that the designed fuzzy control equalization approach performs well.

4.3 Analysis of Simulation Results

It can be seen from the above simulation equilibrium results. When no equalization strategy is added, the maximum operating current of the lithium-ion battery will reach 6A, far exceeding the set safe current. Under the constraints of the fuzzy control strategy proposed in this paper, the maximum operating current of the lithium battery is 3A, which is kept within a safe range. After different initial SOC equalization tests, the proposed fuzzy control equalization strategies can achieve equilibrium and have good adaptability.



(**a**) (**b**)

(**c**) (**d**)

Fig. 12. Different initial SOC equalisation results

5. CONCLUSION

For the equalization control problem of Li-ion battery packs, a fuzzy control technique has been presented. The proposed fuzzy control approach inputs external current and SOC and outputs an appropriate equalization current. The equalization efficiency is increased as much as feasible while maintaining the battery's usual operation. The suggested equalization algorithm has been tested and found to minimize peak current during battery operation by a significant amount, allowing the battery pack to be equalized more safely and quickly.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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