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RESEARCH ARTICLE

# Research on Retired Battery Equalization System Based on Multi-Objective Adaptive Fuzzy Control Algorithm

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**ABSTRACT** In the secondary utilization of retired batteries in energy storage systems, there exists a significant disparity between batteries, rendering the storage battery pack susceptible to issues such as overcharging and overdischarging during the charging and discharging process. These challenges impose limitations on the available capacity of the storage battery system and may even give rise to safety hazards. To tackle these issues, this study proposes the design of a battery equalization system specifically tailored for retired batteries employed in energy storage systems. A multilayer equalization topology based on a buck-boost chopper circuit is introduced, along with a multi-objective adaptive fuzzy control equalization strategy. This strategy integrates the open-circuit voltage-state of charge (OCV-SOC) characteristic curve of the battery and utilizes voltage and SOC as equalization variables. It governs the magnitude of equalization current based on the battery pack's SOC state, enabling effective equalization control of the retired battery pack. Simulation results demonstrate that the proposed equalization strategy does not rely on the precise mathematical model of the battery system. When compared with the mean-difference equalization strategy or the single-variable equalization strategy, it exhibits an enhanced equalization rate. Consequently, it fulfills the practical application requirements for equalizing retired battery packs.

**INDEX TERMS** Retired batteries, active equalization, fuzzy logic control, multi-objective, adaptive.

## ABBREVIATIONS

| | |
|---|---|
| SOC | State-of-charge. |
| BMS | Battery management system. |
| OCV | Open-circuit voltage. |
| OC | Optimal control. |
| MPC | Model predictive control. |
| SMC | Sliding mode control. |
| SIC | Swarm intelligent control algorithms. |
| NNs | Neural networks. |
| GA | Genetic algorithms. |
| FLC | Fuzzy logic control. |
| HPPC | Hybrid Pulse Power Characteristic. |

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## I. INTRODUCTION

In recent years, with the increasing popularity of electric vehicles and hybrid vehicles in China [1], the number of retired power batteries has grown rapidly [2], and the demand for reasonable secondary utilization of retired batteries is very urgent [3]. In general, the capacity of retired electric vehicle batteries is usually 70% to 80% [4] of the rated capacity, and after sorting they can still be used in applications with lower requirements for battery performance, such as energy storage systems [5] and base station power backup [6].

In order to meet the demand for high voltage and large capacity of energy storage systems, batteries are often used in groups in the form of series and parallel connections [7]. However, in the manufacturing process, due to the different manufacturing processes and materials

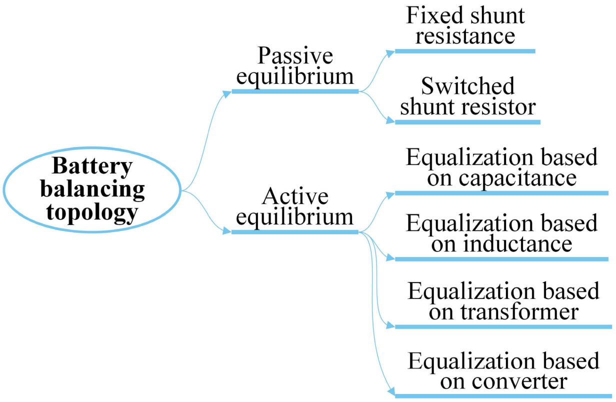


**FIGURE 1.** **Basic equilibrium topology classification.**

used, the initial capacity, internal resistance, self-discharge rate and other performance indicators of the battery differ to different degrees [8], [9], [10]. In the actual operation process, on the one hand, such differences are gradually accumulated and amplified after a long period of battery service; on the other hand, the different operating conditions of the battery lead to different degrees of degradation of its performance parameters, which in turn aggravates the inconsistency of the battery pack [11]. Large inconsistencies can lead to lower available capacity, shorter cycle life, and possibly safety problems due to overcharge and overdischarge [12].

In engineering applications, various methods such as multi-condition sorting are commonly employed to enhance the consistency of a group of batteries. Additionally, the battery equalization function implemented in the BMS (battery management system) is also an effective approach to address the inconsistency among battery cells [13], [14]. The core objective of equalization within the BMS is to achieve a process akin to ‘‘cutting the peaks and filling the valleys’’. This methodology involves the redistribution of surplus energy from cells with higher energy levels to cells with lower energy levels, thus ensuring a harmonious and well-balanced battery pack during its operational performance. As an important part of the battery management system, this technology is important for preventing overcharge and overdischarge, ensuring the available capacity of the battery and prolonging the service life of the battery.

Battery equalization technology mainly includes two parts: the topology structure of equalization circuit and equalization strategy. The former forms a circuit of energy exchange through component links, while the latter controls the equalization circuit through algorithm design. The two parts will be introduced successively below [15].

The basic battery equalization structure can be divided into two major categories: active equalization and passive equalization. Passive equalization, alternatively referred to as energy dissipative equalization, entails the dissipation of excessive energy from higher energy battery cells in the form of thermal energy. This method, which has gained widespread usage in electric vehicles and small-scale energy storage systems, effectively prevents overcharging of individual cells. However, the thermal effect of passive equalization circuit is obvious, and the thermal management problem brought by it has not been effectively mitigated, so further research is still needed. Active equalization, on the other hand, as a non-energy dissipative equalization, refers to the transfer of energy through energy storage elements such as capacitors or inductors, thus reducing the inconsistency problem of the battery pack. According to the different energy transfer elements used, active equalization can be broadly classified into four topologies: capacitor-based, inductor-based, transformer-based, and converter-based, as shown in Figure 1.

Compared with passive equalization, active equalization is more suitable for energy storage systems with higher capacity and larger number of batteries. With the development of new energy storage plants, the equalization topology of energy storage batteries is gradually developing in the direction of more efficient, reliable and economical. Among them, the transformer or converter-based equalization structure has a broad development prospect due to its applicability and expandability [16].

Compared with the transformer-based equalization structure, the converter-based equalization structure has good scalability and high integration, which is one of the key development directions of active equalization. However, there are still problems with the complex circuit design and difficult control of this structure. The commonly used converters in the battery equalization topology mainly contain Cuk circuits, Boost circuits, and Buck-Boost circuits. The literature [17] further proposed an equalization topology based on Buck-Boost chopper circuit, which can achieve equalization between adjacent battery cells by controlling the on/off of switches. However, when it is applied to long battery string equalization, the equalization speed will be affected. In order to solve the inconsistency problems encountered when using large-scale battery strings in series, current equalization systems are moving toward multipolarity and modularity. Using a graph-theoretic approach, some scholars quantified the efficiency of battery equalization systems and found that the more series-connected cell monoliths in a battery pack, the higher the efficiency of multi-layer equalization compared to single-layer equalization [18]. Consequently, a hybrid two-stage equalization topology has been proposed. In this topology, the first stage incorporates a buck-boost chopper circuit-based equalization structure, while the second stage adopts a transformer-based equalization topology. This combination enables cross-cell energy transfer, thereby enhancing the equalization capability and minimizing circuit losses. However, it is worth noting that the fabrication process of the multi-winding transformer used in this topology poses certain challenges. As a result, the

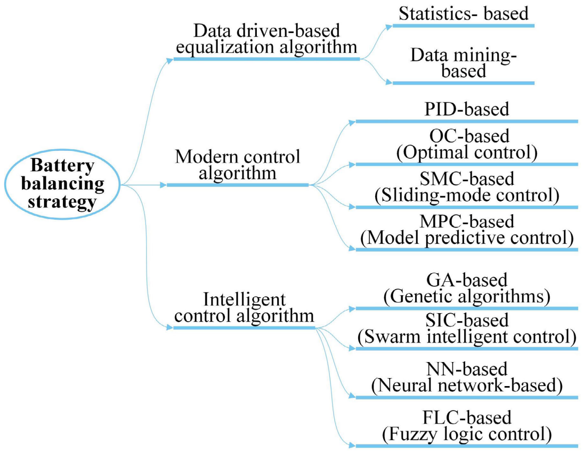


**FIGURE 2.** **Classification of battery equalization strategies.**

transformer is in size, more expensive, and exhibits limited scalability [19].

The safe and efficient operation of the battery equalization system does not only depend on reliable hardware circuits, but the equalization control strategy is also crucial to improve the equalization performance. The battery equalization strategy includes the selection of equalization variables and the selection of equalization control strategy in terms of the selection of equalization variables.

There are two mainstream equalization variables: battery voltage and battery SOC, which correspond to the battery voltage-based control strategy and the battery SOC-based control strategy. Voltage is widely utilized as the equalization parameter in existing techniques due to its ease of acquisition. However, according to the literature [20], employing the external battery voltage as the equalization variable does not fundamentally address the capacity discrepancy among battery cells, nor does it effectively maximize the overall capacity of the battery pack. A comparative analysis of the equalization effect of using voltage and SOC as equalization variables under the same conditions has shown that the latter control is better provided that accurate SOC estimation can be achieved [21]. With the development of battery equalization technology, it is difficult for a single equalization variable to meet the demand of the battery pack, and the equalization strategy based on the fusion of multiple variables gradually becomes the development direction of the equalization strategy.

Under the condition that the equalization circuit and the equalization variables are certain, the equalization effect depends mainly on the choice of the equalization control method. There are three trends in the development of equalization algorithms, and their specific classification is shown in Figure 2.

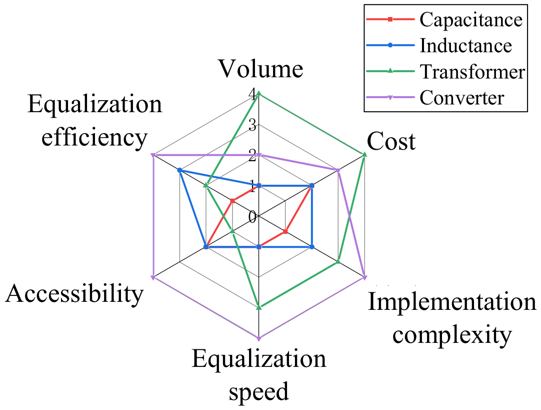
One is the data-driven equalization algorithm, which contains control algorithms based on data statistics and data mining, etc. This particular method is characterized by its simplicity, ease of implementation, and high accuracy in data processing. However, it necessitates precise acquisition and estimation of relevant parameters; otherwise, it may lead to perplexing control logic, such as overbalancing and repetitive equalization, thereby lengthening the equalization duration and diminishing the overall equalization efficiency. For example, some scholars proposed propose to use the mean difference method to improve the equalization efficiency [22], first estimate the of each battery and the average of the battery pack. If the difference between and is greater than the equalization threshold, the equalization will be started until the battery pack reaches the equilibrium. This algorithm can achieve better battery pack consistency and is simple to operate. However, this method often requires comparison with the average variable, which requires high computational resources for the embedded system and is prone to repeated equalization or misequalization. So some scholars [23] proposed to use the range of equalization variables and the operating current as the basis for when equalization starts and stops, and to classify the imbalance situation into three types of too high, too low, or both too high and too low according to the battery pack voltage in order to develop different strategies. To a certain extent, it improves the equalization efficiency, but again requires high computer sampling accuracy.

The second is the equilibrium algorithm based on modern control theory, which contains classical PID control algorithm, OC (optimal control), MPC (model predictive control), SMC (sliding mode control) and so on. These methods are simple in structure, stable and reliable in closed loop and easy to adjust, especially the classical PID control algorithm has been widely used in industrial control field. However, it relies on the establishment of an accurate battery equalization circuit model, and the classical PID control parameters are not variable, which makes it difficult to stabilize the system quickly once sudden changes occur. So some scholars [24] proposed to optimize the proportional and integral parameters of the controller using particle swarm algorithm, and they obtained the control model for estimating the equalization time and current with the absolute error of the battery SOC and the average SOC as the objective function of the battery equalization controller model. The method is iterated by a particle swarm algorithm to obtain the tuned PI controller parameters. Compared with classical PID control, it has simple design, good equalization performance and low power consumption.

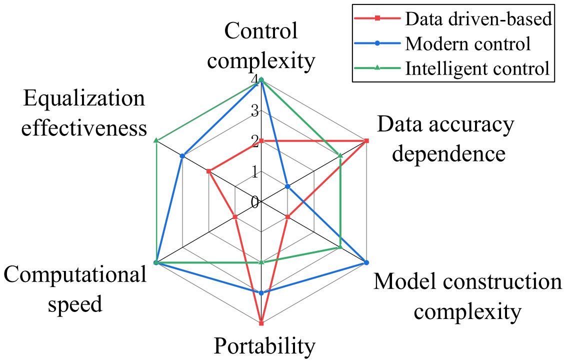
The third is the equilibrium algorithm based on intelligent control theory, which contains SIC (swarm intelligent control algorithms), NNs (neural networks), GA (genetic algorithms), FLC (fuzzy logic control), etc. This type of algorithm does not require complex models and is simple to control; however, it requires a large amount of data support. Currently, it is relatively difficult to obtain equilibrium data and train high-precision models. Among them, FLC algorithm is very suitable for the control of nonlinear systems like batteries because it does not require an accurate mathematical model, and it can make reasonable decisions about the battery equalization system under uncertain external conditions. FLC can shorten the equalization time [25], is robust, has good real-time performance, has simple control parameters, the current can be dynamically adjusted, and has good fault tolerance, which can greatly improve the equalization efficiency. However, since the formulation of fuzzy rules depends on the knowledge and experience of the equalization strategy, insufficient and inappropriate knowledge can lead to output oscillation, which makes the equalization accuracy decrease. The fuzzy threshold method has been proposed in [26] to solve the problems of equalization mis-opening and frequent switching of equalization circuits caused by the fixed threshold method, and FLC is used to dynamically set the voltage threshold to effectively reduce the voltage difference at the battery end and shorten the equalization time. However, since the rule base is based on human experience, the process is relatively complex and subjective errors may exist. FLC is applied not only to the equalization threshold solution but also to the equalization current and other parameters in the equalization strategy, and good results are achieved. Some scholars [27] used the voltage difference between two cells and the cell voltage as the two inputs of FLC. The inference results are converted into numerical output equalization currents to reduce equalization time and improve equalization efficiency and battery pack capacity. Similarly, some scholars proposed [28] to use the cell SOC and SOC difference as inputs and the output as the actual SOC after equalization to achieve the SOC consistency based on FLC in a short time. However, since the battery SOC and battery voltage are not simply linear, it is difficult to make the equalization system optimal by using a single indicator for fuzzy control.

In order to assess and contrast the performance of different categories of active equalization topologies and equalization strategies, an evaluation was conducted. This evaluation involved a comparison of various equalization topologies in terms of their volume, cost, implementation complexity, equalization speed, Accessibility, and equalization efficiency. Additionally, several equalization strategies were compared with regard to their control complexity, data accuracy dependence, model construction complexity, portability, computational speed, and equalization effectiveness. The findings of this evaluation are presented in Figure 3.

As mentioned above, most of the existing equalization techniques use the single cell voltage, SOC or capacity as the equalization target, but the relevant parameters of the battery are collected with errors due to the accuracy of sensors and estimation algorithms, so there are flaws no matter which variable is selected. Moreover, the excessive equalization current at the end of charging and discharging will bring a certain shock to the battery, and if it is not controlled, there may be a danger of overcharging and overdischarging the battery, which affects the health status of the battery. Therefore, in this paper, for the background of retired batteries used in energy storage systems, an active equalization circuit based on multilayer cascaded buck-boost chopper circuits is proposed, and an adaptive fuzzy control control strategy based on multivariate coordination of battery voltage and SOC is designed. Segmented hybrid control is carried out according to the battery operating state, which effectively avoids the occurrence of overcharging and overdischarging as well as mis-equalization of the battery pack. While enhancing the flexibility of equalization, it improves the conversion rate of the equalizer and has good expandability, which is suitable for the use of large-scale retired batteries in energy storage systems, thus realizing the efficient and fast equalization of retired battery packs.



(a) Comparison of battery active equalization topologies



(b) Comparison of battery equalization strategies

**FIGURE 3.** Comparison of battery active equalization topology and equalization strategy.

## II. CIRCUIT TOPOLOGY PRINCIPLE AND PARAMETER DESIGN

### A. EQUALIZATION CIRCUIT PRINCIPLE ANALYSIS

In this paper, the design of the equalization system is implemented using a multilayer equalization topology based on the buck-boost chopper circuit due to the requirement of the large number of retired batteries in use and the need for better scalability. As shown in Figure 4, in the equalization system, A1, A2...... An are the first layer equalization; every two adjacent first layer equalization groups and the equalization sub-modules installed between them form the second layer

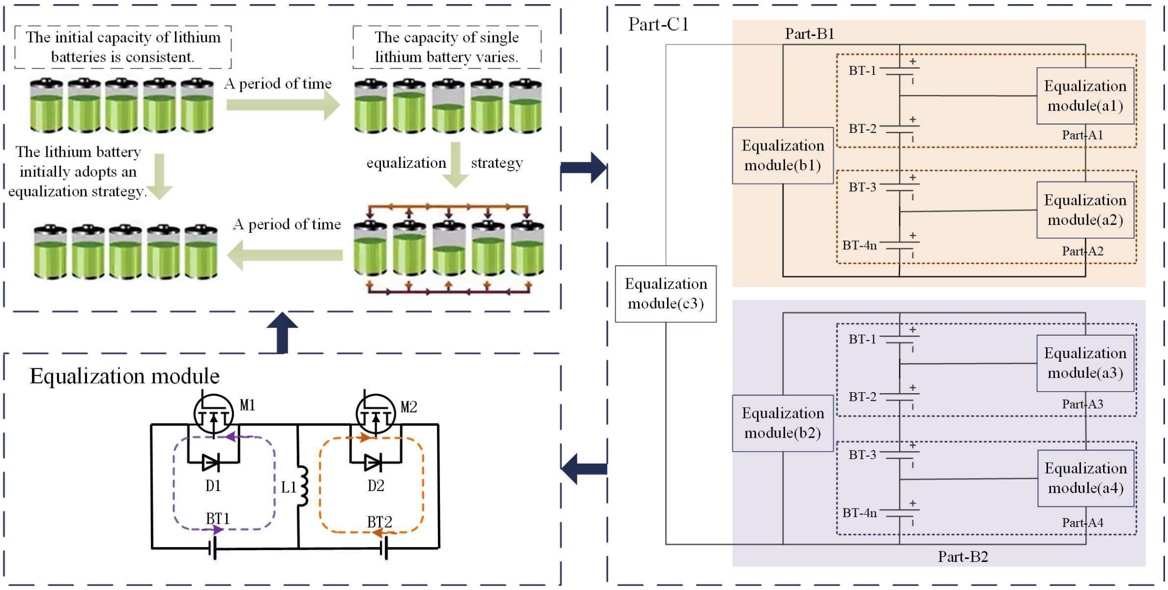


**FIGURE 4.** Battery equalization circuit topology.

equalization group, B1, B2……Bm are the second layer equalization groups. Similar to the pyramid structure, the layered equalization can equalize all the cells in the battery pack at the same time, which is suitable for a large number of cells connected in series and greatly accelerates the equalization speed.

As shown in Figure 4 equalization module, the energy transfer can be done by controlling the on/off of MOSFETs to achieve the equalization between two adjacent batteries or modules. Among them, the power inductor L1 is the energy storage element for energy transfer, and D1 and D2 are the current-continuing diodes connected in reverse parallel at both ends of the MOSFET. Taking the energy of battery BT1 is greater than BT2 as an example, the equalization process is divided into two stages, BT1 discharging and BT2 charging, and the detailed principle is as follows.

1. BT1(battery#1) discharging process, As shown in the purple line of the figure: the energy of BT1 is higher than BT2. the control system sends out a high level signal, the switch tube M1 conducts, BT1, L1 and M1 form a circuit. BT1 energy is stored in the inductor L1, after a period of time, the controller sends a low level signal, M1 disconnects, and the balanced current reaches its maximum value;
2. BT2(battery#2) charging process, As shown in the orange line of the figure: After M1 is disconnected, the continuity diode D2 is turned on, L1, D2 and BT2 form a circuit, and the inductor L1 is used as the power supply to charge BT2. The current gradually decreases from the maximum value and the voltage decays until the voltage at L1 is lower than the sum of the breakdown voltage of BT1 and D1, the equalization current drops to 0 and the charging process ends, at which time the energy stored in the inductor is transferred to BT2. After several cycles of charging and discharging process, the excess power in BT1 is completely transferred to BT2 to achieve the battery equalization state;

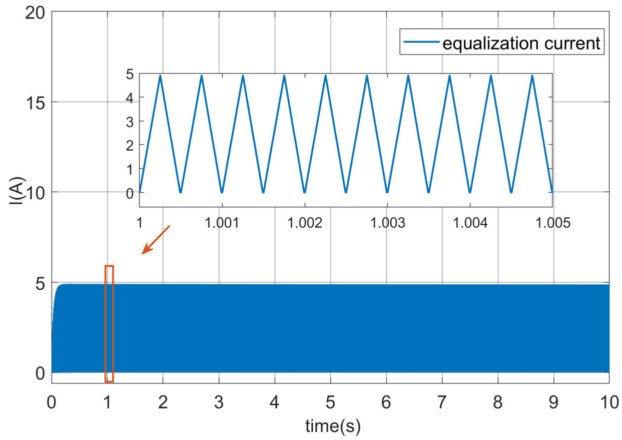


**FIGURE 5.** Evolution diagram of the equalization current.

once the equalization process of class A battery is completed, the equalization circuit of class B will be turned on. the equalization principle of class B circuit is similar to that of class A circuit, by controlling the turning on and off of the equalization modules b1, b2…to realize the equalization control of the battery pack. This equalization principle is also applicable to the equalization circuits of class C, D, E…to meet the application scenario of large number of retired batteries used in groups.

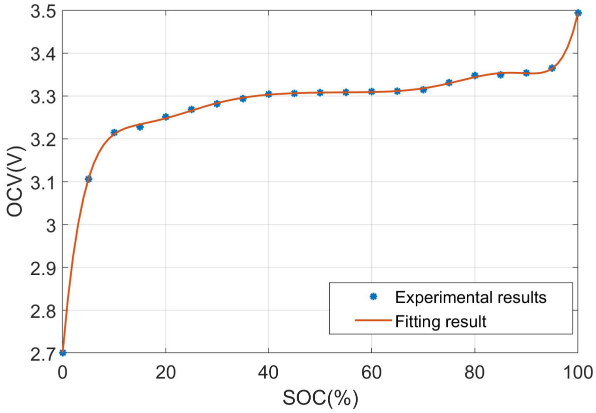


**FIGURE 6.** Cell OCV-SOC fitting curve.

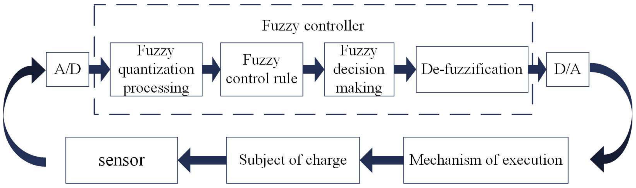


**FIGURE 7.** Control system's architecture.

### B. EQUALIZATION CIRCUIT PARAMETER DESIGN

The energy transfer process of the battery is now quantitatively analyzed to determine the factors influencing the current variation during the equalization process. When the power of battery 1 is higher than that of battery 2, battery 1 is discharged. At this time, the voltages of the two batteries are $V_1$ and $V_2$. The control system sends a control signal to make the controlled switch turn on at a high level. At this time, the charging circuit formed by the inductive battery is a first-order RL circuit that follows the zero-state response mode, and its equation of state is:

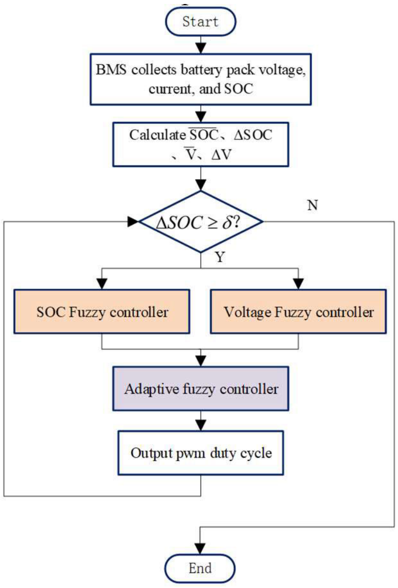
$$V_1 = R_{on} i_L + L\frac{di_L}{dt}, t = 0 \to t_{on} \tag{1}$$

where $R_{on}$ is the total resistance of the discharge circuit when the switch is on, including the line resistance and the on-resistance of the switch. $L$ indicates the inductance of the power inductor used, $i_L$ is the value of the equalization current in the loop, and $t_{on}$ is the length of time the switch is on in the loop. The solution $i_L$ to equation (1) is calculated as:

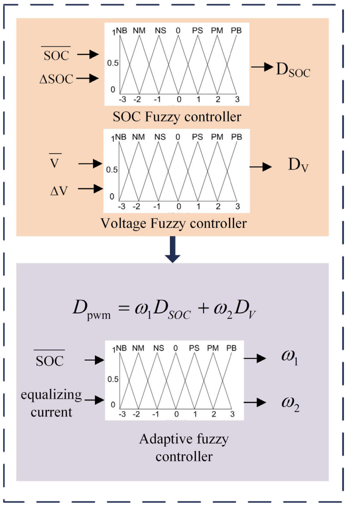
$$i_L = \frac{V_1}{R_{on}} - \frac{V_1}{R_{on}} e^{-t\frac{R_{on}}{L}} = \frac{V_1}{R_{on}}\left(1 - e^{-t\frac{R_{on}}{L}}\right), \ t = 0 \to t_{on} \tag{2}$$

According to this equation, the current has a maximum value when the switch reaches its maximum opening time.

$$i_{\max} = i_L = \frac{V_1}{R_{on}}\left(1 - e^{-t_{on}\frac{R_{on}}{L}}\right) \tag{3}$$



(a) Fuzzy control flow



(b) Input/output of fuzzy controller

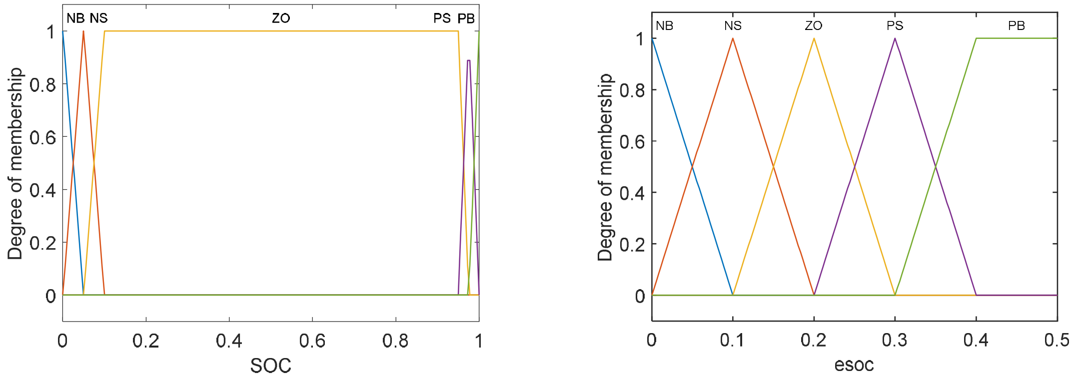
**FIGURE 8.** Control system's flowchart.

When the switch is closed to a low level, the circuit response equation is:

$$i_L = i_{\max} e^{-(t-t_{on})\frac{R_{off}}{L}} - \frac{V_2+V_D}{R_{on}}\left[1 - e^{-(t-t_{on})\frac{R_{off}}{L}}\right], \quad t = t_{on} \to t_{off} \tag{4}$$

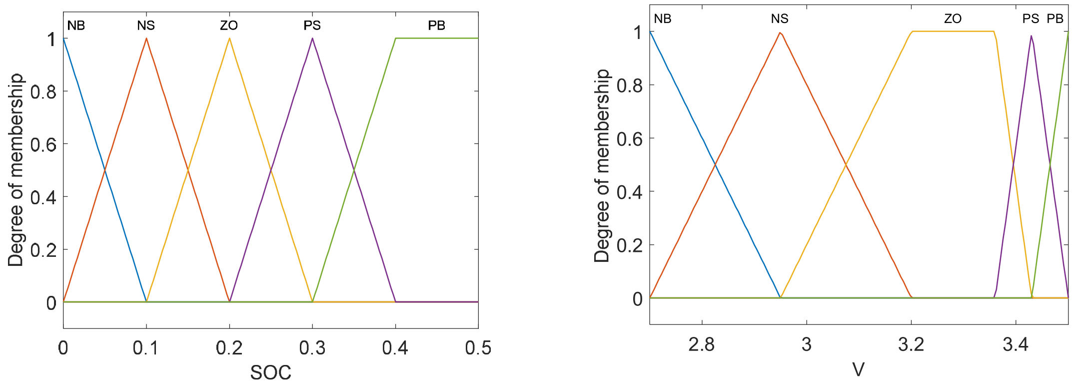
where $V_D$ is the tube voltage drop of the diode and $R_{off}$ is the total resistance of the charging circuit when the switch is turned off.

From the derivation formula, it can be seen that the equalization system in the equalization adjustment, the change of its equalization current is always exponential. Due to the high switching frequency of MOSFET, the charging and discharging time of the inductor is very short, and the internal resistance of the original in the circuit is very small when it is on, so the exponential function of the current in the



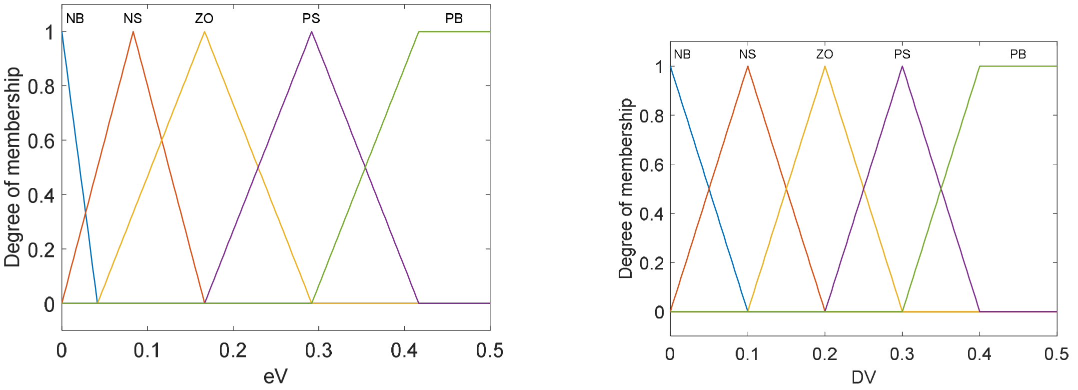
(a) SOC average

(b) SOC Difference



(c) SOC control duty cycle

(d) Voltage average



(e) Voltage difference

(f) Voltage controlled duty cycle

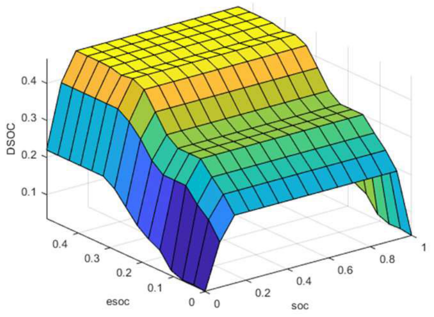
**FIGURE 9.** **SOC and voltage fuzzy controller input-output affiliation function.**

inductor with time can be approximately transformed into a linear relationship as follows:

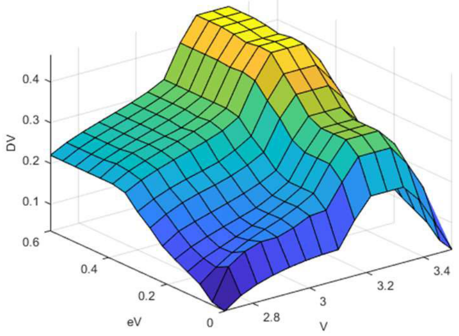
$$i_{\max} \approx \frac{V_2}{L} t_{on} = \frac{V_2}{L} DT \tag{5}$$

Combined with the object of study 18650 lithium iron phosphate battery, rated capacity of 1Ah, rated voltage of 3.2 V, internal resistance of 30-40 mΩ. To ensure the safety of the battery, the equalization current is set to about 5 A, the switching frequency is 2 kHz. Determine the equalization current and switching frequency can be selected after the energy transfer power inductance value of 0.16 mH, ignoring the line resistance in the equalization module. According to the current level of power electronics manufacturing, the on-state resistance of the control switch is 10 mΩ. The simulink simulation model is built according to the above parameters as shown in Figure 5.

From the simulation results, it can be seen that the peak current in the equalization process is about 5 A, which can meet the efficiency of the equalization process of the equalization system and the requirements of the safety performance of the battery pack at work. In actual use, according to the actual capacity and voltage standard of the battery pack, the period of the control signal and the size of



(a) SOC fuzzy control input and output 3D



(b) Voltage fuzzy control input and output

**FIGURE 10.** Input and output 3D coordinate map.

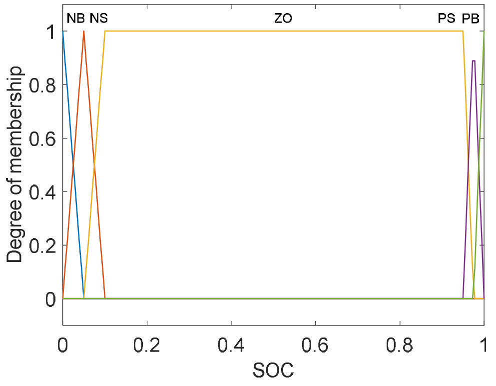
the power inductor can be flexibly adjusted to change the size of the equalization current, so as to apply to different voltage and capacity standards of the battery pack.

## III. EQUILIBRIUM CONTROL STRATEGY BASED ON ADAPTIVE FUZZY CONTROL

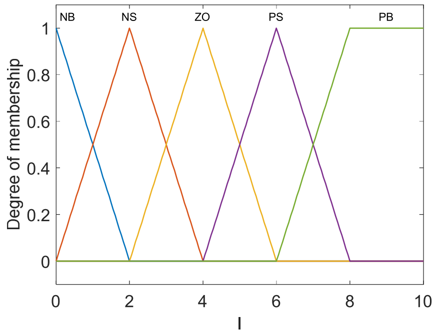
### A. EQUILIBRIUM VARIABLE SELECTION

By analyzing the development status of battery pack equalization technology, it can be seen that most of the research literature uses battery voltage or SOC as equalization variables, and a few use remaining battery capacity as equalization variables, which basically control the start-stop of the equalization system by setting the equalization variable threshold. However, in practice, there are limitations in using whatever parameters as equalization variables, and these limitations are especially prominent in the equalization of retired battery packs where the inconsistency is more severe.

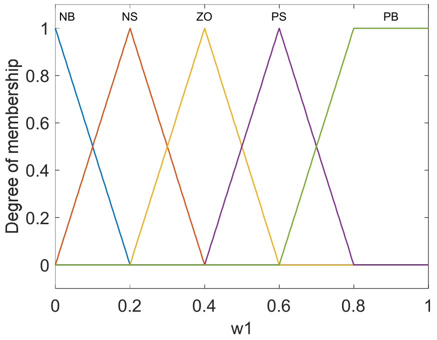
In this paper, the expression of the OCV-SOC function of the battery is obtained by conducting HPPC compound pulse experiments on 18650 LiFePO4 battery and then polynomial fitting by matlab tool. Figure 6 shows the results of the 9th order polynomial fit, which shows that the battery has a large rate of change of open-circuit voltage in the two intervals of SOC values from 0% to 10% and 95% to 100%, while the open-circuit voltage changes smoothly in the interval of SOC values from 10% to 95%. If the voltage is the only variable



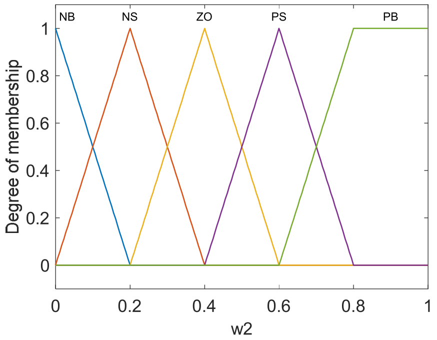
(a) SOC average



(b) Equalization current



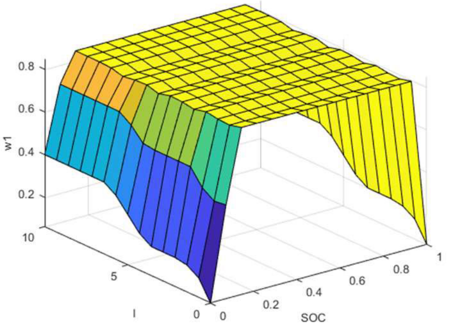
(c) $\omega_1$



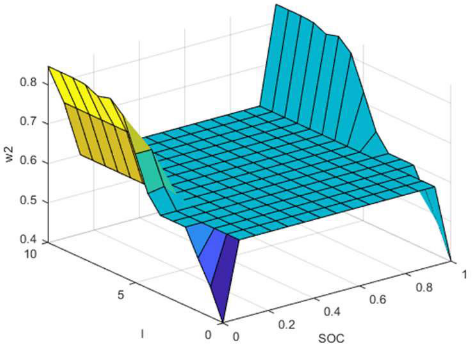
(d) $\omega_2$

**FIGURE 11.** Adaptive fuzzy controller input-output affiliation function.

when the SOC is in the 10% to 95% interval, the larger change range of SOC only produces a slight change in voltage, which puts higher requirements on the accuracy and response



(a) $\omega_1$



(b) $\omega_2$

**FIGURE 12.** **Adaptive fuzzy control input and output 3D coordinate diagram.**

speed of the voltage measurement instrument and may cause inefficiency or mis-equalization of the equalization system, and the voltage equalization is more limited at this time. If the SOC is the only variable when the SOC is in the interval of 0% to 10% and 95% to 100%, the SOC is the only variable, and the SOC estimation itself has error, which may cause the low battery to be over-discharged and the high battery to be over-charged, and the SOC equalization is more limited at this time. Therefore, this paper proposes a multi-objective equalization strategy based on the SOC and voltage of the battery, which selects different equalization variables according to the different states of the battery. The inconsistency between retired batteries is improved to some extent.

### B. BATTERY EQUALIZATION CONTROL STRATEGY

In this paper, a multivariable coordinated control equalization scheme based on voltage and SOC is proposed by studying the principle of equalization circuit topology and analyzing the advantages and disadvantages of different equalization variables. Since there is no clear functional relationship between the equalization variables parameters voltage and SOC of the battery and duty cycle in the equalization system, and the equalization system is a complex time-varying system, and the fuzzy control does not depend on an accurate mathematical model, it is suitable for a nonlinear system like battery equalization. Figure 7 shows the composition of the fuzzy controller. The basic structure of the fuzzy controller includes four parts: knowledge base, fuzzy inference, fuzzification, and defuzzification. The fuzzy control firstly, the operator or expert writes the fuzzy rules according to the test, then fuzzifies the real-time signal from the sensor, uses the fuzzified signal as the input of the fuzzy rules, completes the fuzzy inference, and adds the output quantity obtained after inference to the actuator.

In order to take into account the equalization rate and the battery safety, the SOC fuzzy controller and the voltage fuzzy controller are designed in this paper. The membership function of triangle and trapezoid is selected, the parameter domain is divided into 5 parts, and $5 \times 5 = 25$ control rules are formulated for each fuzzy controller, taking into account the control effect and computational complexity. After that, the output of the SOC fuzzy controller and voltage fuzzy controller is weighted and reorganized by designing an adaptive fuzzy controller, and the final output expectation duty cycle is used to control the PWM signal wave of the equalization circuit to determine the equalization current size, and the equalization control process is shown in Figure 8.

#### 1) VOLTAGE AND SOC FUZZY CONTROLLER DESIGN

Both the SOC fuzzy controller and the voltage fuzzy controller contain two inputs and one output, both of which are the SOC or voltage mean and difference of the adjacent battery cells, and the output is the duty cycle to control the equalization current. The theoretical domain of SOC mean $\overline{SOC}$ is $\{0, 0.05, 0.1, 0.95, 0.975, 1\}$, and the theoretical domain of voltage mean $\overline{\mathrm{V}}$ is $\{2.7, 2.95, 3.2, 3.3, 3.4, 3.5\}$. the theoretical domain of SOC difference $\Delta$ SOC is $\{0, 0.1, 0.2, 0.3, 0.4, 0.5\}$, and the theoretical domain of voltage difference $\Delta\mathrm{V}$ is $\{0, 0.05, 0.1, 0.4, 0.5\}$. The theoretical domain of the output desired duty cycle D of the SOC fuzzy controller and voltage fuzzy controller is $\{0, 0.1, 0.2, 0.3, 0.4, 0.5\}$. Define the names of fuzzy language variables as NB (negative large), NS (negative small), ZO (zero), PS (positive small), PB (positive large). The affiliation functions of input and output variables of SOC fuzzy controller and voltage fuzzy controller are shown in Figure 9.

Considering the safety of battery operation and the performance of the equalization system, the fuzzy control rules are obtained by debugging the equalization control system several times: When $\overline{SOC}$ is large or small, for the purpose of battery protection, use a smaller equalization current to avoid overcharging and overdischarging the battery. If the $\Delta$ SOC is large at this time, the duty cycle can be increased appropriately to ensure the safe operation of the battery while increasing the equalization rate as much as possible. When $\overline{SOC}$ is in a medium situation, a larger equalization current should be used to quickly eliminate the inconsistency between the batteries. The voltage fuzzy controller is similar to the SOC fuzzy controller, and the specific fuzzy rules are shown in Table 1.

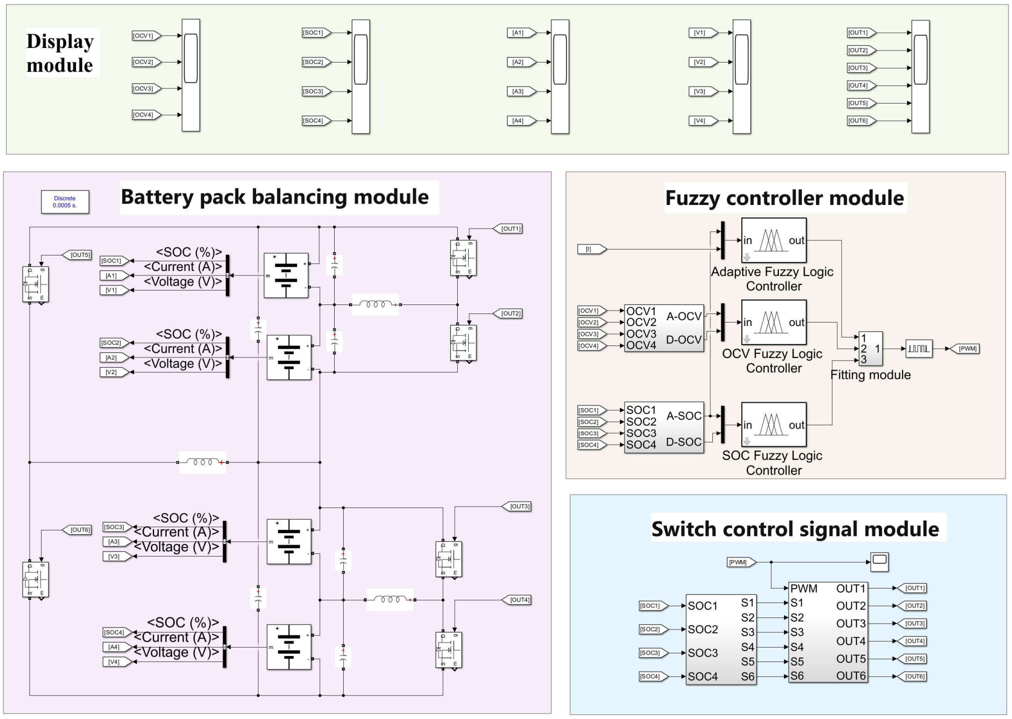


**FIGURE 13.** Equilibrium system simulation model.

**TABLE 1.** SOC fuzzy controller's rules.

| $D_{SOC}$ $\Delta SOC$ / $SOC$ | NB | NS | ZO | PS | PB |
|---|---|---|---|---|---|
| NB | NB | NB | NS | ZO | ZO |
| NS | NS | ZO | ZO | PS | PS |
| ZO | ZO | PS | PS | PB | PB |
| PS | NS | ZO | ZO | PS | PS |
| PB | NB | NB | NS | ZO | ZO |

The SOC fuzzy controller and voltage fuzzy controller are solved by the inverse fuzzification of the center of gravity method, and their input and output 3D coordinates are shown in Figure 10.

### 2) ADAPTIVE FUZZY CONTROLLER DESIGN

The adaptive fuzzy controller contains two input quantities and two output quantities, the input quantities are the mean SOC value and the equalization current value of the adjacent battery single cell or group, and the output quantities are the weight coefficients $\omega_1$ and $\omega_2$ of the output duty cycle of the SOC fuzzy controller and the voltage fuzzy controller, respectively. after the weight assignment of the adaptive fuzzy controller, the final output desired duty cycle D is:

$$D = \omega_1 D_{SOC} + \omega_2 D_V \tag{6}$$

where $D_{SOC}$ and $D_V$ are the duty cycles of the SOC fuzzy controller and voltage fuzzy controller outputs, respectively; $\omega_1$ and $\omega_2$ are the weight coefficients of the adaptive fuzzy control outputs with values not greater than 1.

**TABLE 2.** Adaptive fuzzy controller's fuzzy rules.

| $\omega_1/\omega_2$ $i$ / $SOC$ | NB | NS | ZO | PS | PB |
|---|---|---|---|---|---|
| NB | NB/ZO | NS/PS | NS/PS | ZO/PB | ZO/PB |
| NS | NS/PS | ZO/PS | ZO/PS | PS/PB | PS/PB |
| ZO | ZO/PS | ZO/PS | ZO/PS | ZO/PS | ZO/PS |
| PS | NS/PS | ZO/PS | ZO/PS | PS/PB | PS/PB |
| PB | NB/ZO | NS/PS | NS/PS | ZO/PB | ZO/PB |

The $D_{SOC}$ and $D_V$ are recombined with corresponding weights by $\omega_1$ and $\omega_2$, indicating that the equalization system is controlled coordinately with both SOC and voltage equalization variables at any moment, and whether SOC equalization or voltage equalization is dominant is selected according to the current state of the battery pack. The theoretical domain of $\overline{SOC}$ is set as {0, 0.05,0.1, 0.95,0.975, 1}, the theoretical domain of equalization current i is {0, 2, 4, 6, 8, 10}, and the theoretical domains of weight coefficients $\omega_1$ and $\omega_2$ are {0, 0.2, 0.4, 0.6, 0.8, 1}. The adaptive fuzzy controller input-output affiliation function is shown in Figure 11.

The fuzzy control rules of the adaptive fuzzy controller are developed according to the OCV-SOC curve of the battery: When the SOC value is very small or very large, hope that the voltage equalization is the main and equalization current is as small as possible. If the feedback equalization current is large, the duty cycle should be reduced to lower the equalization current. When the SOC value is medium, it is hoped that the

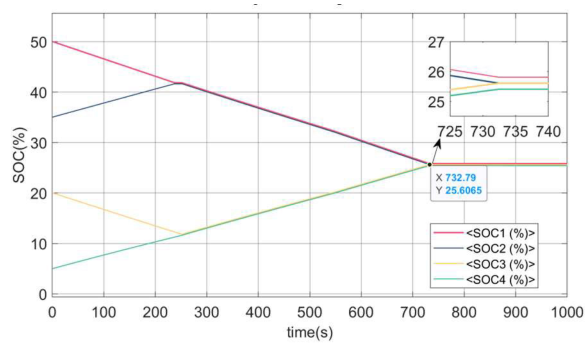
SOC equalization is the main and the equalization current can be larger, and the equalization speed should be accelerated, the specific control rules are shown in Table 2.

The adaptive fuzzy controller is solved by the inverse fuzzification of the center of gravity method, and its input-output three-dimensional coordinate diagram is shown in Figure 12.

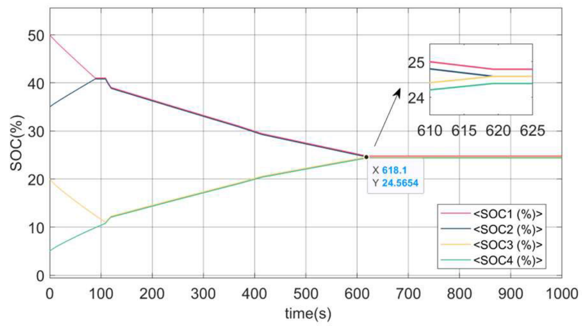
## IV. EQUALIZATION CONTROL SYSTEM MODEL BUILDING AND SIMULATION VERIFICATION

Based on the above analysis of the proposed equalization circuit structure and equalization strategy, a circuit simulation model is constructed in Matlab/Simulink platform with 4 batteries as an example, as shown in Figure 13. The model contains series battery pack balancing module, switch control signal module, fuzzy controller module, and display module. When the equalization starts, according to the state of the battery pack, the three fuzzy controllers output duty cycle to the switch signal control module to turn on the corresponding channel switch in the switch matrix, so as to realize the energy exchange. The specific parameters of the simulation are described in Section II-B of this paper: LiFePO4 nominal voltage 3.2 V, charging cutoff voltage 3.5 V, discharging cutoff voltage 2.7 V, battery internal resistance 32 m$\Omega$, battery rated capacity 1 Ah, MOSFET switching frequency 2 KHz, intra-group power inductance 160 $\mu$H, inter-group power inductance 320 $\mu$H, MOSFET on-resistance 0.1 $\Omega$, internal resistance of continuing diode 0.01 $\Omega$ and on-state voltage drop 0.7 V.

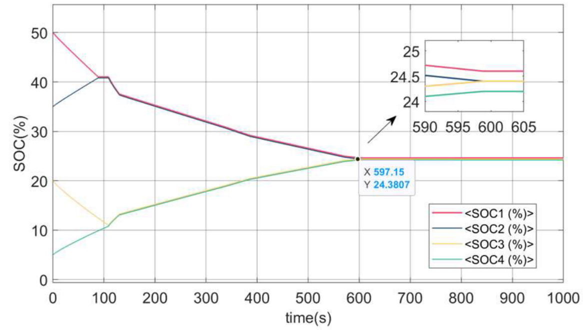
After a lot of literature research, most of the current equalization control algorithms are data-based control algorithms, and the mean interpolation method is one of them, which is simple to implement and scalable, and is now widely used. However, it requires high resource requirements for the embedded system and requires frequent comparison with the average voltage, which is prone to overbalance and repeated equalization. Moreover, various battery equalization methods currently employed in engineering applications all focus on equalization rate, which is also a significant evaluation metric for equalization strategies. This parameter determines the ability to address the issue of battery inconsistency within a series-connected battery pack within a relatively short period of time. The equalization rate is determined by the equalization current, but if the equalization current is too high, it will lead to overcharge and overdischarge at the end of charging and discharging, which will affect the battery life and create safety hazards. In consideration of the above problem, this paper simulates the equalization of three methods: the data-based mean difference algorithm, the single target control method, and the proposed algorithm in three states: charging, discharging, and netting. In addition, this paper designs the equalization simulation at the end of battery charging and discharging in order to prevent the overcharge and overdischarge of the battery caused by the excessive equalization current.



(a) Mean difference method



(b) Single-objective equalization algorithm



(c) The algorithm proposed in this paper

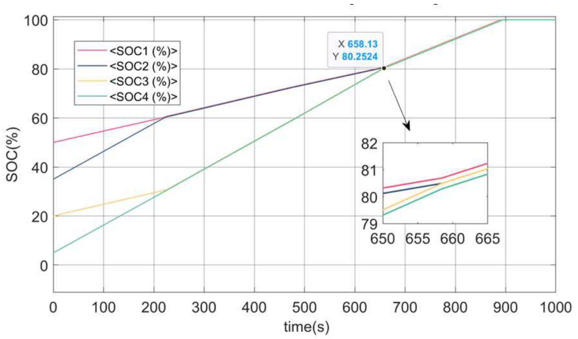
**FIGURE 14.** **Battery pack resting state equalization.**

### A. BATTERY PACK RESTING STATE EQUALIZATION SIMULATION

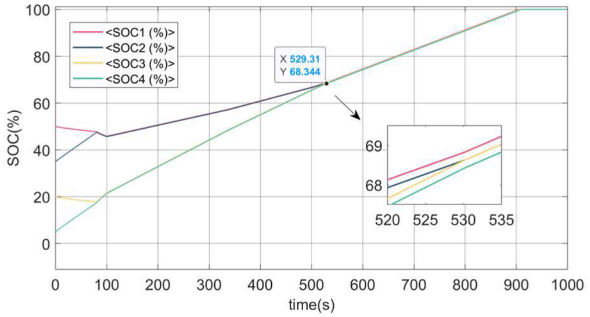
When the battery is stationary, the battery pack does not interact with the outside world for energy at this time. The initial values of the simulation are set as follows: the SOC value of battery B1 is 50%, battery B2 is 35%, battery B3 is 20%, battery B4 is 5%, and the equalization threshold of battery pack is SOC>0.2%. Comparing the control algorithm proposed in this paper with the mean difference method and the single objective fuzzy control method, the battery pack SOC variation curves during the equalization process are shown in Figure 14. It can be seen that the battery pack basically achieves the equalization effect after 732.79 s, 618.10 s and 597.15 s, respectively.

### B. BATTERY PACK CHARGE STATE EQUALIZATION SIMULATION

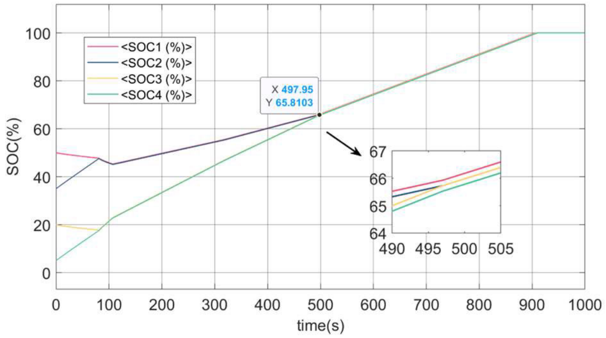
Charge equalization of the battery pack, the initial battery value setting is the same as the static equalization: Battery



(a) Mean difference method



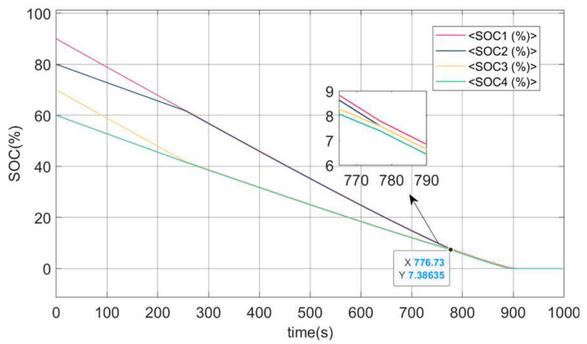
(b) Single-objective equalization algorithm



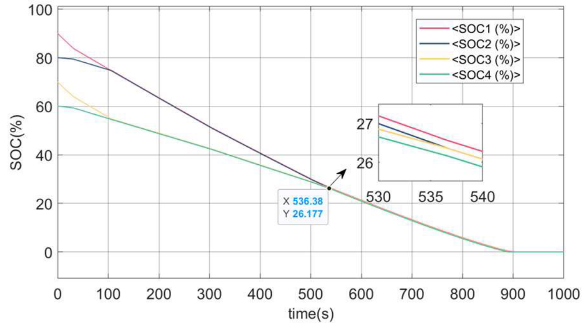
(c) The algorithm proposed in this paper

**FIGURE 15.** **Battery group charging state balance.**

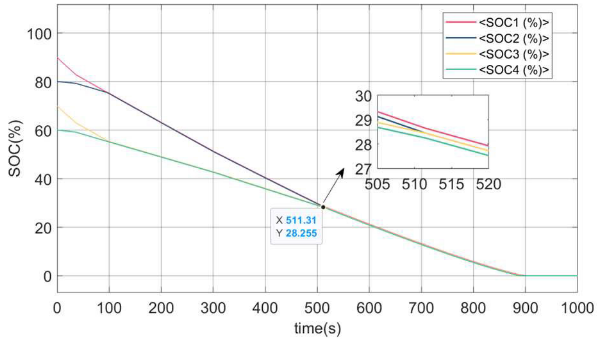
B1 is 50%, Battery B2 is 35%, Battery B3 is 20%, Battery B4 is 5%, and the charging current is set to 3C, and the equalization threshold of the battery pack is greater than 0.2%. After the equalization is turned on, the SOC change curves of each battery under the three equalization control strategies are shown in Figure 15, which shows that the battery pack basically reaches the equalization effect after 658.13 s, 629.31 s and 497.95 s, respectively.



(a) Mean difference method



(b) Single-objective equalization algorithm



(c) The algorithm proposed in this paper

**FIGURE 16.** **Battery pack discharge state equalization.**

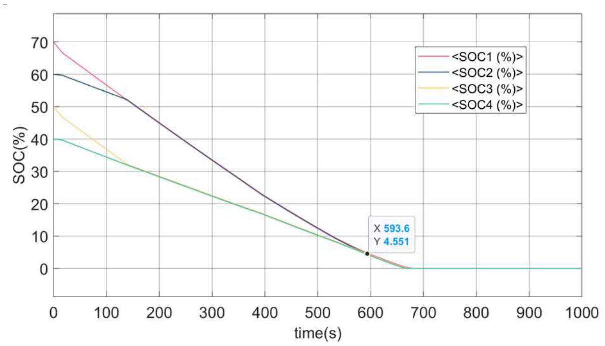
**TABLE 3.** **Comparison of equilibrium time results.**

| Battery pack status | Mean difference method(s) | Single-objective equalization algorithm(s) | The algorithm proposed in this paper(s) |
|---|---|---|---|
| resting | 732.79s | 618.10s | 597.15s |
| charge | 658.13s | 529.31s | 497.95s |
| discharge | 776.73s | 536.38s | 511.31s |

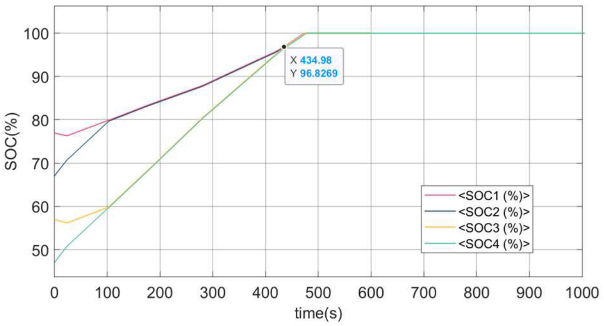
### *C. BATTERY PACK DISCHARGE STATE EQUALIZATION SIMULATION*

To discharge the battery pack for equalization, the initial value of the battery is set as follows: Battery B1 is 90%, Battery B2 is 80%, Battery B3 is 70%, Battery B4 is 60%, and the threshold of battery equalization on is SOC greater than 0.2%. After the equalization is turned on, the SOC change curves of each battery under the three equalization control strategies are shown in Figure 16, which shows that the battery pack basically reaches the equalization effect after 776.73 s, 536.38 s and 511.31 s, respectively.

Through the above comparison, it can be seen that the proposed multi-objective adaptive fuzzy controller is more effective in dealing with the equalization problem of the nonlinear battery system, and the equalization effect is significantly improved compared with both the mean difference control method and the single objective control method. the comparison results are shown in Table 3, and the equalization completion times are 597.15 s, 497.95 s,



(a) Discharge state



(b) Charge state

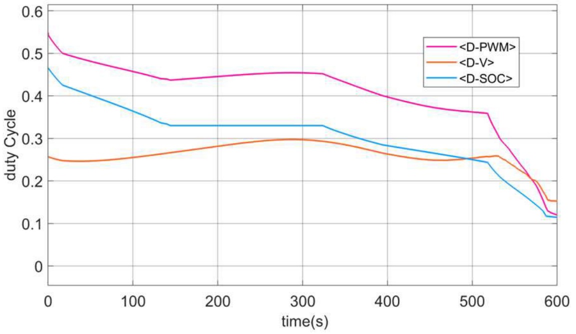
**FIGURE 17. SOC change curve during charging and discharging.**

and 511.31 s for the three states, respectively. therefore, for the the same nonlinear equilibrium system, the proposed multi-objective adaptive fuzzy control method achieves good results.

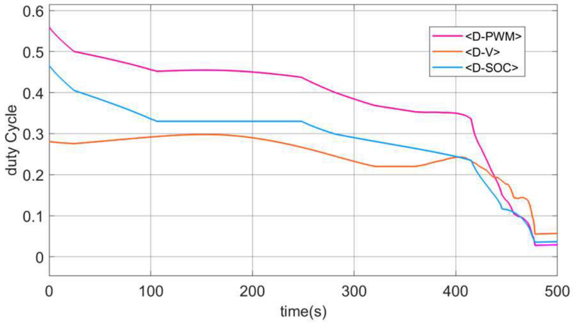
### D. SIMULATION OF THE EQUALIZATION EFFECT OF THE BATTERY PACK AT THE END OF CHARGING AND DISCHARGING

When the battery pack is about to be charged and discharged, if the equalization current is not controlled at this time, the larger equalization current will lead to overcharge and overdischarge of the battery pack, which will affect the service life of the battery, and there are also hidden dangers such as explosion and combustion. In order to prevent similar phenomena, the equalization strategy proposed in this paper is designed by fuzzy rules, and the fuzzy controller will output different duty cycles to change the size of the equalization current according to the different stages the battery is in.

According to the above content, the equalization simulation of charging and discharging tail period is set. Discharge tail simulation: set the initial battery value B1 to 70%, B2 to 60%, B3 to 50%, and B4 to 40%; Charge tail simulation: set the initial battery value B1 to 47%, B2 to 57%, B3 to 67%, and B4 to 77%.The battery pack equalization opening threshold is greater than 0.2% SOC. The simulation results are shown in Figure 17-figure 19. It can be seen that in the over-discharge suppression simulation, the battery pack reaches the same after 592.76 s, and the SOC of the battery

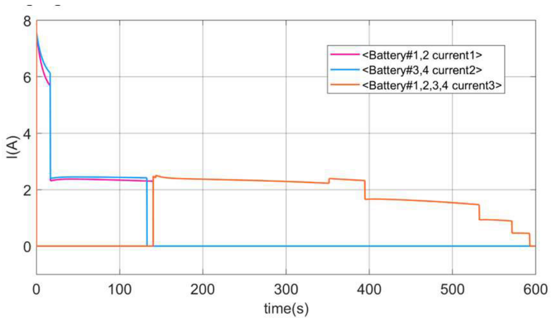


(a) Discharge state

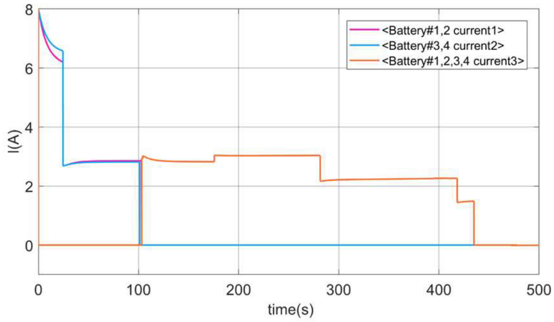


(b) Charge state

**FIGURE 18. Fuzzy controller output duty cycle during charging and discharging.**



(a) Discharge state



(b) Charge state

**FIGURE 19. Equalization current effective value during charging and discharging.**

pack is 4.4% at this time, the duty cycle of the fuzzy controller output decreases from 0.53 at the beginning to about 0.15, and the effective value of the equalization current decreases from 7.5 A to about 0.5 A. The trend of the charging state is similar to that of the discharge. It can be seen that the control strategy proposed in this paper can effectively prevent the overcharge and overdischarge of the battery pack while ensuring the equalization rate.

## V. CONCLUSION

For the large number of retired battery equalization systems and the need for good scalability, this paper adopts a multilayer equalization topology based on buck-boost chopper circuit. And on this basis, an equalization strategy based on multi-objective adaptive fuzzy control algorithm is proposed, which takes the battery voltage and battery SOC as well as the equalization current as inputs to segmentally equalize the battery system, using multiple variables to complement each other and coordinate control, overcoming the inability of a single equalization variable to eliminate the inconsistency of retired batteries under complex and variable operating conditions, and improving the control effect of the equalization system. The simulated results show that the equalization times of the control strategy described in this paper are 597.15 s, 497.95 s, and 511.31 s for the three states of resting, charging, and discharging, respectively, which increase the equalization rate by 18.5%, 38.0%, and 34.2% compared with the mean difference control method, and by 3.39%, 5.92%, and 4.67% compared with the single objective fuzzy control method. At the same time, during the equalization process, the equalization current can be changed with the state of the battery, which effectively prevents the overcharge and overdischarge of the battery and the mis-equalization phenomenon, and the equalization energy transfer efficiency is high, which improves the consistency between the single battery and the available capacity of the battery is greatly increased. Due to the limited theoretical level and research time of the authors, there are still some defects in the equalization control system. In the future, the development of the equalization circuit hardware system will be carried out, and the battery temperature and internal resistance will be used as the reference index of the equalization system to further improve the service life of the battery pack.

## REFERENCES

[1] C. Minyi, Z. Ei, L. Jing, W. Kangli, J. Kai, and Z. Min, "Review on balancing topology of lithium-ion battery pack," *Proc. CSEE*, vol. 41, pp. 5294–5311, Jan. 2021.

[2] K.-Y. Lo, Y.-M. Chen, and Y.-R. Chang, "Bidirectional single-stage grid-connected inverter for a battery energy storage system," *IEEE Trans. Ind. Electron.*, vol. 64, no. 6, pp. 4581–4590, Jun. 2017.

[3] S. S. Williamson, A. K. Rathore, and F. Musavi, "Industrial electronics for electric transportation: Current state-of-the-art and future challenges," *IEEE Trans. Ind. Electron.*, vol. 62, no. 5, pp. 3021–3032, May 2015.

[4] J. Li, Y. Li, C. Lv, W. Zhao, Y. Wu, and S. Ma, "Key technology of retired batteries' screening and clustering under target of carbon neutrality," *Power Syst. Technol.*, vol. 46, no. 2, pp. 429–441, 2022.

[5] Y. Yang, C. Xie, and C. Zhu, "Research on active equalization method of retired lithium-ion batteries for the echelon utilization," *Adv. Technol. Elect. Eng. Energy*, vol. 40, no. 6, pp. 50–56, 2021.

[6] Y. Wang, D. Meng, Y. Chang, Y. Zhou, R. Li, and X. Zhang, "Research on online parameter identification and SOC estimation methods of lithium-ion battery model based on a robustness analysis," *Int. J. Energy Res.*, vol. 45, no. 15, pp. 21234–21253, Dec. 2021.

[7] M. Zhan, J. Ke, and T. Wu, "Retired battery equalization method based on isolated half-bridge converter," *Electron. Meas. Technol.*, vol. 45, no. 17, pp. 7–13, 2022.

[8] Z. Y. Liu, Y. H. Wu, P. F. Li, and P. C. Li, "Battery pack equalization method based on Cuk chopper circuit," *Chin. J. Sci. Instrum.*, vol. 49, no. 2, pp. 72–88, 2019.

[9] Q. Yu, Y. Huang, A. Tang, C. Wang, and W. Shen, "OCV-SOC-temperature relationship construction and state of charge estimation for a series–parallel lithium-ion battery pack," *IEEE Trans. Intell. Transp. Syst.*, vol. 24, no. 6, pp. 6362–6371, Jun. 2023.

[10] Q. Yu, L. Dai, R. Xiong, Z. Chen, X. Zhang, and W. Shen, "Current sensor fault diagnosis method based on an improved equivalent circuit battery model," *Appl. Energy*, vol. 310, Mar. 2022, Art. no. 118588.

[11] D. Brunner, A. K. Prasad, S. G. Advani, and B. W. Peticolas, "A robust cell voltage monitoring system for analysis and diagnosis of fuel cell or battery systems," *J. Power Sources*, vol. 195, no. 24, pp. 8006–8012, Dec. 2010.

[12] S. M. Lukic, J. Cao, R. C. Bansal, F. Rodriguez, and A. Emadi, "Energy storage systems for automotive applications," *IEEE Trans. Ind. Electron.*, vol. 55, no. 6, pp. 2258–2267, Jun. 2008.

[13] Q. Yu, C. Wang, J. Li, R. Xiong, and M. Pecht, "Challenges and outlook for lithium-ion battery fault diagnosis methods from the laboratory to real world applications," *eTransportation*, vol. 17, Jul. 2023, Art. no. 100254.

[14] Y. Yang, L. Zhao, Q. Yu, S. Liu, G. Zhou, and W. Shen, "State of charge estimation for lithium-ion batteries based on cross-domain transfer learning with feedback mechanism," *J. Energy Storage*, vol. 70, Oct. 2023, Art. no. 108037.

[15] Y. Chen, X. Liu, X. Yang, and J. Zou, "Overview of active equalization topologies for series connected batteries," *Power Supply*, vol. 5, no. 5, pp. 28–36, 2013.

[16] J. R. Galvão, L. B. Calligaris, K. M. de Souza, J. D. Gotz, P. B. Junior, and F. C. Correa, "Hybrid equalization topology for battery management systems applied to an electric vehicle model," *Batteries*, vol. 8, no. 10, p. 178, Oct. 2022.

[17] Y. Ma, P. Duan, Y. Sun, and H. Chen, "Equalization of lithium-ion battery pack based on fuzzy logic control in electric vehicle," *IEEE Trans. Ind. Electron.*, vol. 65, no. 8, pp. 6762–6771, Aug. 2018.

[18] Y. Chen, X. Liu, H. K. Fathy, J. Zou, and S. Yang, "A graph-theoretic framework for analyzing the speeds and efficiencies of battery pack equalization circuits," *Int. J. Electr. Power Energy Syst.*, vol. 98, pp. 85–99, Jun. 2018.

[19] Y. Chen, X. Liu, Y. Cui, J. Zou, and S. Yang, "A multiwinding transformer cell-to-cell active equalization method for lithium-ion batteries with reduced number of driving circuits," *IEEE Trans. Power Electron.*, vol. 31, no. 7, pp. 4916–4929, Jul. 2016.

[20] Y. Zheng, M. Ouyang, L. Lu, J. Li, X. Han, and L. Xu, "On-line equalization for lithium-ion battery packs based on charging cell voltages: Part 2. Fuzzy logic equalization," *J. Power Sources*, vol. 247, pp. 460–466, Feb. 2014.

[21] M. Einhorn, F. V. Conte, C. Kral, and J. Fleig, "A method for online capacity estimation of lithium ion battery cells using the state of charge and the transferred charge," *IEEE Trans. Ind. Appl.*, vol. 48, no. 2, pp. 736–741, Mar. 2012.

[22] M. M. Hoque, M. A. Hannan, and A. Mohamed, "Voltage equalization control algorithm for monitoring and balancing of series connected lithium-ion battery," *J. Renew. Sustain. Energy*, vol. 8, no. 2, pp. 457–468, Mar. 2016.

[23] F. Altaf, B. Egardt, and L. J. Mårdh, "Load management of modular battery using model predictive control: Thermal and state-of-charge balancing," *IEEE Trans. Control Syst. Technol.*, vol. 25, no. 1, pp. 47–62, Jan. 2017.

[24] M. M. Hoque, M. A. Hannan, and A. Mohamed, "Optimal algorithms for the charge equalisation controller of series connected lithium-ion battery cells in electric vehicle applications," *IET Electr. Syst. Transp.*, vol. 7, no. 4, pp. 267–277, Dec. 2017.

[25] G.-C. Hsieh, L.-R. Chen, and K.-S. Huang, "Fuzzy-controlled Li-ion battery charge system with active state-of-charge controller," *IEEE Trans. Ind. Electron.*, vol. 48, no. 3, pp. 585–593, Jun. 2001.

[26] Z. Liu, Y. Ma, Q. Sun, and W. Tang, "Optimization of battery equalization strategies based on dynamic fuzzy threshold," *China Mech. Eng.*, vol. 28, pp. 624–629, Mar. 2017.

[27] Y. S. Lee and J. Y. Duh, "Fuzzy-controlled individual-cell equaliser using discontinuous inductor current-mode Cuk convertor for lithium-ion chemistries," *IEE Proc.-Electr. Power Appl.*, vol. 152, pp. 1271–1282, Sep. 2005.

[28] B. Wang, F. Qin, X. Zhao, X. Ni, and D. Xuan, "Equalization of series connected lithium-ion batteries based on back propagation neural network and fuzzy logic control," *Int. J. Energy Res.*, vol. 44, no. 6, pp. 4812–4826, May 2020.

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