A Novel Battery Equalization Method Base on Fuzzy Logic Control Considering Thermal Effect

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Abstract. In order to avoid battery over-charges and over-discharges and improve the battery pack capacity, a passive equalization controller based on fuzzy logic control (FLC) is proposed to reduce the impact on inconsistency in manufacture and use processes of battery pack. A cell’s state of charge (SOC) difference and its temperature is chosen as the FLC’s input and the balance current is chosen as the FLC’s output. The advantage of this FLC is can reach a larger balancing current and control the batteries temperature at the same time compare with average SOC controller and switch controller. Simulation results show that the equalization strategy based on FLC can achieve battery pack balance in a shorter time in a lower finish temperature. This equalization strategy can provide battery management system (BMS) designer a higher performance control strategy on the basis of the existing hardware platform.

1. Introduction

Lithium-ion batteries have the advantage of high power and energy density, low self-discharge rate, long lifetime and low environment pollution compared with other kind of battery, so it becomes one of the most important battery types[1]. Because single battery cell’s voltage and output current is limited by its electrochemical characteristics, battery cells must be connected in parallel and serially to provide enough voltage and current. However, due to the inconsistency of the battery cells when manufacturing, there exist imbalance among the battery pack[2]. Moreover, the uneven temperature distribution and uneven aging through the entire battery string will aggravating battery pack inconsistency. Hence, the voltages of each cell are inhomogeneous during charging and discharging[3].

State of charge (SOC) is one of the most important parameters in EV to present how much remaining energy can be used[4]. SOC difference caused by battery inconsistency is a critical problem of battery pack. Over-charge and over-discharge which can lead to battery cell damage because of Lithium-ion battery’s chemical properties must be avoided. Therefore, charging process should be stop when one of the battery cells reach the upper SOC bound and discharging process should be stop when one of the battery cell’s SOC reach 0%. It maybe happens that one of the cells is discharged completely while there still remain plenty of energy in the other cells. That means the packs’ capacity is limited by the cell with minimum SOC. The battery pack actual capacity is decided by the rechargeable and useable capacity. Thus, it’s necessary to propose a battery pack equalization method to keep each cell’s SOC in a same level to increase the useable and rechargeable capacity and maximum battery pack capacity[5].
Many researches have been proposed to realize the battery pack balance. According to the energy transfer mode, present equalization approaches can be divided into passive equalization (PE) and active equalization (AE). AE transmit energy from the cells with higher SOC to energy storage components, and the cells with lower energy are allowed to retrieve the exceed energy from those components. According to the type of energy storage medium, AE can be classified as capacitor base AE, inductor base AE and converter base AE. According to the energy transfer mode, AE can be classified as cell to cell, cell to pack, cell to module, cell to pack to cell.

PE transfer the energy form the cell with higher SOC or voltage into heat through shunting resistor. According to the different type of shunting resistor, PE can be divided into fixed shunting resistor, switched shunting resistor and analog shunting resistor. As shown in Figure.1, the balancing current will be larger in the cell with higher voltage which can reduce the voltage difference between each cell. This approach has the advantage of simple circuit structure and lower control cost. But the problem associated with this trend is that the equalization current is uncontrollable and it’s will lead to additional power loss in the shunt resistor[6]. The controlled shunting resistor[7] is shown in Figure.2 where a switch or relay serially connected with cell and its shunting resistor. When one cell’s SOC or voltage is higher than the other, the switch will be shunted and the exceed charge will be consumed by the resistor. Comparing with fixed shunt resistor method, controlled shunting resistor is more efficient, reliable and safety. This controller is very cheap and simple, and is wildly used in EVs including Tesla. But, the same with fixed shunt resistor PE, this controller remove exceed energy by resistor that will increase the cell current and cause temperature increment of battery and resistor. Most battery manufacturers recommend that the credible operating temperature of present EV lithium-ion battery are: discharging at -20 to 55°C and charging at 0 to 45°C[1].

The above researches provided a number of valuable results to solve the problem of battery cells inconsistency. However, most of prior studies have focused on new AE circuit structure design or new AE control stage design. But AE circuit has a problem of complex structure which will cause cost and failure rate. What’s more, it difficult to integrate the AE into the integrated chip (IC) because of the complex structure. Meanwhile, a number of battery monitoring IC with PE function is designed by semiconductors manufactures. Passive shunting resistor switch or switch driver is integrated into those IC that can help battery management system (BMS) manufacturer realize PE easily. However, as mentioned before, PE transfer exceed energy into heat. The energy consumption mode brings a problem that if equalization current (EC) is too large, a lot of heat will be generated in a short time and the temperature of battery cell and BMS will exceed safety limits. As a result, the EC is limited in hundred mA level and it will take a long time to finish equalization. In order to solve the contradiction between equalization time and battery safety, this study attempts to propose a FLC whose input is SOC difference and battery temperature and output is EC.
First, this study builds a series connection cell pack (SCCP) model considering battery thermal effect during charging and discharging which is constructed on the basis of research[8]. Then, a series connection cell equalization controller (SCCEC) is proposed. This controller resolves the EC base on SOC difference and temperature. Finally, the SCCEC is applied to the simulation and shows that this controller can realize equalization in an acceptable time and the temperature of battery is under control.

The rest of this paper is arranged as follows. Section 2 introduce the thermal and electrical model of the battery cell. In section 3, FLC for SOC and temperature base equalization is proposed. Section 4 discusses the simulation result. Finally, the conclusions and prospects are presented.

2. Battery Model of the Equalization System

2.1. Thevenin Equivalent Circuit Model

In order to simulate the battery reaction under charging and discharging, the electrochemical model and equivalent circuit model is employed to calculate. The electrochemical model which is based on the battery real electrochemical reaction is can’t applied in the real BMS because of high complexity and huge amount of computation[9]. Meanwhile, the equivalent model including Rint model, Thevenin equivalent circuit, second-order equivalent and higher order equivalent is more wildly used in BMS. Comparing with other equivalent model, Thevenin model has enough accuracy with a relatively low amount of computation. The main function of the model is to simulate the voltage and temperature response when charging and discharging. Panchal et al.[10] introduce that the Thevenin equivalent circuit model can provide a precise calculating result of temperature and voltage. What’s more, Thevenin model is applied successful in battery equalization and identification field[9, 11, 12].

![Thevenin equivalent circuit model](image)

As shown in figure 3, Thevenin model is consist of voltage source $U_{oc}$, ohmic resistance $R_0$, and a resistance capacitance (RC) loop circuit. The RC loop circuit comprise a polarization resistor $R_p$ and a polarization capacitance $C_p$, which can reflect the influence of battery polarization. According to Kirchhoff’s law, the response voltage can be calculated as follows:

$$u_i = u_{oc} - iR_0 - u_p$$

(1)

$$C_p \frac{du_p}{dt} + \frac{u_p}{R_p} = i$$

(2)

The parameters mentioned above is functions of SOC and temperature. The physical signals look-up table in Matlab is a useful tool to computes an approximation to the function given input data break points. The look-up table calculate the output based on the input grid lookup using the interpolation and extrapolation method. In order to describe the battery better, Hybrid Pulse Power Characteristic (HPPC) test should be applied under several typical temperature which is chosen as the break points. Then, the battery parameters can be identified by the test data in different temperature and different SOC. Those parameters in any SOC and any temperature can be determined using nonlinear least squares interpolation method which can minimize the sum of squared error. Hence, in order to ensure the
simulate model can reflect the real voltage response, those parameters can be searched in a two-dimensional look-up tables as follows:

\[ R_0 = R_0(SOC, T) \quad (3) \]
\[ R_p = R_p(SOC, T) \quad (4) \]
\[ C_p = C_p(SOC, T) \quad (5) \]
\[ U_\infty = U_\infty(SOC, T) \quad (6) \]

As the formula shows, the SOC and temperature are look-up tables' input and battery parameters are outputs. The SOC is the ratio of the remaining capacity to the nominal capacity as follows:

\[ SOC(t) = SOC(t_0) - \frac{1}{C_n} \int_{t_0}^{t} i(\tau)d\tau \quad (7) \]

Where \( SOC(t) \) and \( SOC(t_0) \) respectively donate the SOC at time \( t \) and the initial SOC at \( t_0 \), \( C_n \) donate the current capacity of the battery, and \( i \) donate the working current which is negative during discharging and positive during charging. There are lots of researches provide the approach to calculate SOC. Coulomb counting, integrate the current output from cell over time during run time, is the most common and simple technique to calculate SOC. Because coulomb counting does not take current measurement errors into consideration, the cumulative error will increase with time. The SOC-OCV correlation curve is the most effective approach to elimination the cumulative. Fortunately, there is no measurement error when simulation in Matlab. As a result, coulomb counting is chosen as the method to computing real time SOC.

2.2. Heat Generating and Transfer in Battery

Many battery models without thermal influence were built in current literature. However, the battery parameters, including voltage, capacity, ohmic resistor and so on, will vary with temperature. So, it’s necessary to add a thermal model to the equivalent circuit model.

A large amount of heat which will lead to battery internal temperature increase is generated during the charging and discharging process due to ion migration, chemical reaction and so on. It is generally considered that the heat production of the battery is composed of four parts: the enthalpy heat generated by internal electrochemical reactions \( Q_r \), Joule heat generated by internal resistance \( Q_J \), polarization heat generated by polarization internal resistance \( Q_p \), the reaction heat generated by electrolyte decomposition \( Q_s \). The enthalpy \( Q_r \) is endothermic while charging and is exothermic while discharging and the total heat of endothermic process and exothermic process is equal to each other. The polarization heat \( Q_p \) of batteries is generated by the migration of lithium ions between positive and negative electrodes, and the hindrance effect of electrode active materials on ions is polarization internal resistance. As a result, the polarization heat present as polarization resistance heat. The reaction heat \( Q_s \) is small enough that can be ignored when calculate the heat production while the battery working in a normal condition. Hence, the total heat production of battery can be calculated as Formula(8):

\[ Q = Q_r + Q_J + Q_p \quad (8) \]

Sato et al.[13] analysis the thermal behavior of batteries and provide the formula to calculate these three kinds of heat:

\[ Q_r = T(-\delta \Delta G / \delta T) = \frac{3600Q_1I}{F} \quad (9) \]

Where \( \Delta G \) is Gibbs's free energy variation, \( T \) is the absolute temperature, \( Q_1 \) represents the algebra of positive and negative heat production while chemical reaction, \( I \) is battery current, \( F \) is Faraday constant which is 96484.5 \( \text{C/mol} \).

\[ Q_p = I^2R_p \quad (10) \]
\[ Q_j = I^2R_j \quad (11) \]
Where $R_p$ and $R_e$ respectively represent ohmic internal resistance and polarization internal resistance, $I$ is battery current. Put the Faraday constant and these three kinds of heat into Formula(8), the total heat production can be present as:

$$Q = 0.014QI + I^2R_p + I^2R_e$$  \hspace{1cm} (12)$$

In generally, the operating temperature range of Lithium-ion power battery is -20~50°C, so that the enthalpy heat has little effect to total heat production. As Formula(12) shows, comparing with polarization heat and joule heat, the enthalpy heat is small enough. Moreover, the enthalpy heat can cancel out each other during charging and discharging. In order to simplify the calculation and increase simulating speed, the total heat production can be computed as:

$$Q = I^2R_p + I^2R_e$$  \hspace{1cm} (13)$$

This paper assumed that the internal battery temperature is uniform and consider the average temperature as the battery temperature. Battery cells contract with other cells and air during use. Cells will absorb heat if the temperature is higher than others and will liberate heat in contrast. The main mode of heat transmission between cell and cell is heat conduction, which can be calculate as:

$$q = \frac{A\lambda}{\delta} (t_{w1} - t_{w2})$$  \hspace{1cm} (14)$$

Where $A$ is contract surface area, $\lambda$ is thermal conductivity, $\delta$ is the length of heat transfer between two cells and $t_{w1}$, $t_{w2}$ respectively present the temperature of two cells. The heat transfer from the cell with higher temperature to the cell with lower temperature.

The outermost battery cell of pack is directly contact with environment and convective heat transfer with air. The heat transfer through the outside of the outermost battery cell can be computed by Newton’s law of cooling:

$$q = hA(t_w - t_j)$$  \hspace{1cm} (15)$$

Where $h$ is heat transfer coefficient, $A$ is heat transfer surface area, and $t_w$ is cell’s temperature and $t_j$ environment’s temperature. In these two kinds of modes, heat conduction and thermal convection can be regarded as overcoming heat transfer by thermal resistance $R_H$ which can be presented as $\delta/A\lambda$ when heat conduction and $1/hA$ when thermal convection. As a result, the temperature of battery cells can be calculated by solving the heat equation:

$$C_T \frac{dT}{dt} = -\frac{T - T_w}{R_H} + Q$$  \hspace{1cm} (16)$$

Where $C_T$ is heat capacitance of cell, $Q$ is the power produced by the cell. Assume that the temperature of battery cell is $T_0$ at time $t_0$, applying a Laplace transformation to Formula(16):

$$T(s) = \frac{QR_H + T_w + T_0R_HC_Ts}{s(1 + C_TR_Hs)}$$  \hspace{1cm} (17)$$

Where the meaning of the variables is explained before. In order to get the temperature response in time domain, applying a Laplace inverse transformation to Formula(17):

$$T(t) = QR_H + T_w + (T_0 - QR_H - T_w)e^{-\frac{t}{C_TR_H}}$$  \hspace{1cm} (18)$$

2.3. The Simulink Model for Battery

The main parameters of a battery pack, including the ohmic resistance, polarization resistance, polarization capacitance, output voltage, SOC and temperature, to analyze the working state is presented as before. The Thevenin equivalent circuit model can be established by the HPPC experiment under different temperature, which can provide some look-up tables to the model. The parameters of Thevenin model can be searched in the initial SOC and temperature condition through those look-up tables when the simulation is start. Then, different load current can be applied to battery Simulink model that can calculate the temperature and SOC of battery through the method shows in 2.1 and 2.2. Furthermore,
the calculated temperature and SOC can provide the basis to the look-up tables. As a result, the working condition of a battery can be simulated in real time. The Simulink model has been tested by Huria and Wang et al.[8, 14]. Their result shows that the model has a high accuracy comparing with the actual experiment.

As shown in Figure 4, the Simscape model of the Thevenin equivalent circuit is consist of a voltage source, a first order RC block unit, a temperature calculation unit and some auxiliary components. The initial parameters are set at the start of simulation. The voltage source can calculate the SOC through coulomb counting and provide the voltage through the lookup table. The heat generating is calculated at the first order RC block. Finally, the temperature calculation unit sum up the dissipate power produced by the ohmic resistor and polarization resistor and calculate the temperature of the battery through the method proposed in 2.2.

3. Battery Model of the Equalization System

3.1. Process of SCCEC
The traditional control method is hard to applied in battery pack equalization controller because the equalization control system is a nonlinear, time-varying system and the relationship between battery pack imbalance and EA is not easy to quantitative analysis. Corresponding to it, the battery pack imbalance and EA can be divided into several levels easily that is an important step in FLC. What’s more, FLC is an intelligent algorithm with a clear and simple structure that can solve the problem of nonlinear, time-varying. As a result, FLC is employed to SCCEC.

In this paper, the PE with some switches circuit is designed to implement the SCCEC. First, the threshold of SOC difference $ΔSOC_i$ and temperature $T_i$ should be set. The battery working condition should be set at the start of simulate. Then, the equalization controller should acquire the voltage, current and temperature of battery, which is the basis of equalization controller. Next, according to the acquired voltage and current, the SOCs of each cell can be calculated by coulomb counting. SOC difference $ΔSOC_i$ between the cell to be equalized and the cell with the minimum SOC can be calculated. During the process of charging and discharging, the equalization based on FLC should be applied one control cycle by another if the SOC difference is lower than the threshold or the temperature is higher than the threshold. Finally, the equalization will stop when the charging and discharging process is stop. The
block diagram of the passive equalization control algorithm based on FLC for SCCP is shown in Figure 5.

Figure 5. Software flow chart of equalization controller based on FLC.

3.2. Fuzzy Logic Control Strategy
In order to realize fast equalization in a safety temperature, FLC is employed to compute the equalization current in SCCEC. Generally, the FLC consist of five parts: fuzzification, data base, rule base, inference machine and defuzzification. FLC plays a nonlinear mapping role between inputs and outputs. The inputs of FLC, which are numerical value instead of fuzzy set, will converted to fuzzy set by the fuzzier using membership function. Then, the fuzzy set will be used to calculate the fuzzy result by inference machine. The knowledge base has two basic function: the first is determine which rules are involved in the current input, the second is use the input and the rule base to deduce the result. Finally, the defuzzified is used to convert the fuzzy result into crisp values. The scheme of the FLC is shown as follow:

Figure 6. Scheme of the FLC.

Generally, the inputs of a FLC should reflect the concerned factors, and the FLC can compute a satisfactory control result. In order to eliminating SOC inconsistency between batteries and ensure the battery pack safety at the same time, the SOC difference, as shown in Formula(19), and the temperature can be chosen as the input of FLC.

\[
\Delta SOC = SOC_i - SOC_{\text{min}}
\]  
(19)
Where $SOCi$ is the $i$th cell’s SOC, $SOC_{min}$ is the minimum SOC in the string. And the output of FLC is equalization current.

Membership function is a mathematical tool that can describe the membership relation of an element, such as SOC difference, to a fuzzy set for characterizing fuzzy sets. Because the ambiguity of this relationship, it will be described by the values from interval $[0,1]$ instead of the two values of 0 and 1, indicating the "true degree" of the element belonging to a certain fuzzy set. According to the basic fuzzier process, the input and output parameters can be divided into some different level such as small, medium and large. The membership function of FLC which is based on the lots of experiments and theoretical analysis is shown as Figure 7. Figure 7(a) shows the membership of SOC difference which is divided into small (DS), medium (M) and large (DL). Figure 8(b) shows the membership of temperature which using TL, TM and TH to represent the temperature of battery cell is low, medium and high. Figure 8(c) shows the membership of the output, equalization current. The fuzzy set CS, CM, CL are respectively representing the equalization current is small, medium and large. The trapezoid fuzzy membership is chosen as the membership of FLC because its simple form and high performance.

The fuzzy rules, the core of FLC, are sets of fuzzy conditional statements based on the practical experience. The fuzzy rules of SCCEC based on FLC is shown in Table 1. The form of fuzzy rules can be expressed with “IF… THEN…” statement. For example, the rule “IF $\Delta SOC$ is DS and Temperature is TL, THEN $I_{equ}$ is CS” means the output current will be small under the inputs of small $\Delta SOC$ and low temperature.

![Figure 7. Membership function of FLC.](image)

**Table 1. Fuzzy Rule of FLC**

| $\Delta SOC$ | Temperature | DS | DM | DL |
|--------------|-------------|----|----|----|
| $TL$         | CS          | CM | CL |
| $TM$         | CS          | CM | CM |
| $TH$         | CS          | CS | CS |
These rules describe the relationship between the SOC difference and the temperature. If the temperature is high, the EA should be small whatever how large SOC difference is because the safety is the most important thing. If the temperature is medium and the SOC difference is large, the equalization should be medium to improve the equalization speed. If the temperature is medium and the SOC difference is not so large, the equalization current should still be small. If the temperature is low, the equalization current is depending on the SOC difference to maximize the equalization speed. That means if the SOC difference is small, medium or large, the equalization can be small, medium or large corresponding. The switching surface of the FLC is shown as Figure 8.

![Figure 8. Decision surface of FLC.](image)

The output of the fuzzy inference machine is fuzzy linguistic which is cannot be used as the output of FLC. Therefore, the defuzzification, a mapping from fuzzy space to exact value space, is necessary for FLC to convert fuzzy linguistic into exact value. In this paper, centroid method is employed as the defuzzification method that transfer fuzzy linguistic into output current. The centroid method is computed as Formula (20).

$$I_{equ} = \frac{\int \mu_e(y)yd\mu}{\int \mu_e(y)d\mu}$$ (20)

Where $\mu_e(y)$ is the fuzzy linguistic of equalization current and $I_{equ}$ is the value of equalization current.

### 4. Simulation Result and Discussion

Mean-difference algorithm in statics state and HPPC working condition is simulated to test and verify the control effect of FLC for SCCEC. The series connection battery string is consisting of eight cells which is power-oriented 31Ah lithium-ion cells of NMC chemistry whose parameters were obtained in [8]. The capacity and initial SOC of each cell are shows in Figure 9. The initial SOC of these respective cells are 0.92, 0.97, 0.98, 0.95, 0.98, 0.90, 0.99, 0.89. Besides, the ambient temperature is set as 20°C.

![Figure 9. The capacity and initial SOC of cells.](image)
The temperature and SOC variation of the series battery cells in the standing static (without any working condition) under different passive equalization algorithm including switch control algorithm, mean difference control and FLC are simulated. The mean difference control algorithm should calculate the mean value of all cells and provide an equalization current for the cells whose SOC is larger than the mean SOC.

The equalization time of SCCEC based on FLC is 2,241s and maximum temperature of all cells is 20.32°C. The equalization time of mean difference control algorithm is 3,227s and maximum temperature is 20.38°C. Comparing with FLC, the equalization time of mean difference control algorithm has increased by 43% and the temperature rise is higher than FLC. Besides, as shown in Figure 10(c), the mean difference control algorithm has the problem of over equalization because it’s impossible to make the SOC of each cell is exactly the same. Therefore, the cell with a little higher SOC will be equalized that will lead to the SOC of this cell will lower than the average SOC. The SOC of cells alternates to become lower. As a result, the equalization will be continue applied in battery string that will lead to energy consumption and temperature raising ceaselessly.

Figure 10. Response of SCCEC in stand static based on FLC. (a) SOC difference between cell and the cell with lowest SOC; (b) Temperature of each cell; (c) SOC of each cell.

Figure 11. Response of SCCEC in stand static based on mean difference control. (a) SOC difference between cell and the cell with lowest SOC; (b) Temperature of each cell; (c) SOC of each cell.
In order to verify the control effect better, a relative extremes HPPC working condition is employed to test the SCCEC algorithm. The battery string is discharged by pulse current of 10C and the discharging experiment is last 20,000s that can present the control and temperature performance of the algorithm. The equalization time of SCCEC based on FLC under HPPC is 2,454s and the maximum temperature of all cell is 34.05°C. The equalization time of mean difference algorithm is 4,826s and the maximum temperature of all cell is 35.23°C. The result shows that the FLC can shortening the equalization time by 49.1% comparing with mean difference algorithm. Besides, the maximum temperature rise under FLC is 8.40% lower than the temperature rises under mean difference algorithm. Improving the equalization current of mean difference algorithm can increase the equalization speed but will lead to temperature rise that will damage the battery. What’s more, the SOC of battery cell using FLC at the end point is 38.26% and is 21.63% using mean difference algorithm. That means FLC can reduce the energy dissipate effective. The reason why the temperature of cells is divided into four levels is that it’s more difficult to dissipate heat for the center cell.

![Figure 12](image_url1)

**Figure 12.** Response of SCCEC in HPPC based on FLC. (a) SOC difference between cell and the cell with lowest SOC; (b) Temperature of each cell; (c) SOC of each cell.

![Figure 13](image_url2)

**Figure 13.** Response of SCCEC in HPPC based on mean difference control. (a) SOC difference between cell and the cell with lowest SOC; (b) Temperature of each cell; (c) SOC of each cell.
The energy efficiency is an important parameter to battery equalization algorithm. The energy efficiency of battery equalization algorithm can be calculated as:

$$\eta = \frac{\sum_{i=1}^{S} \int u_{ni}(t)i_{ni}(t)dt}{\sum_{i=1}^{S} \int u_{ni}(t)i_{ni}(t)dt + \sum_{i=1}^{S} \int u_{di}(t)i_{di}(t)dt}$$ (21)

Where \(u_{ni}(t)\) and \(i_{ni}(t)\) respectively represents the total voltage and current of the \(i\)th cell in time \(t\), \(i_{di}(t)\) is the current pass through the shunt resistor.

Urban Dynamometer Driving Schedule (UDDS) can represents city driving conditions and is used to vehicle testing. In order to verify the energy efficiency of SCCEC, this paper respectively use the UDDS and HPPC condition to discharge battery pack. The dissipated energy and the total energy of different control algorithm is shown in Figure 14:

**Figure 14.** Energy and dissipated energy of SCCEC based on different control algorithm. (a) Dissipated energy of SCCEC in HPPC; (b) Total energy of SCCEC in HPPC; (c) Dissipated energy of SCCEC in UDDS; (d) Total energy of SCCEC in HPPC.

At the end of simulation, the energy consumed by the HPPC in 20000s using mean difference is 209.18kJ and is 167.40kJ using FLC. The energy efficiency for the mean difference controller and FLC is calculated as 70.32% and 88.85%. Analogously, the energy efficiency under UDDS of mean difference controller and FLC is 83.96% and 88.99%. As a result, the energy efficiency of FLC is improved by 18.53% in HPPC condition and by 5.03% in UDDS.

The experimental result shows the SCCEC based on FLC can reduce the equalization time under an acceptable temperature comparing with mean difference algorithm. In addition, the FLC can provide a high utilization rate of battery power.

5. Conclusion
A passive equalization method which is designed to improve the consistency of battery string based on FLC is proposed and a simscape SCCP model considering thermal effect is built in this paper. The
A simscape model is built to reflect the battery response, including voltage, SOC, temperature and so on, under some specific load. In order to realize the equalization in a short time under a safety temperature, the SOC difference and the cell temperature is chosen as the input of FLC. The mean difference algorithm was simulated to reflect the superiority of FLC. The simulation results show that the proposed method can improve the consistency for the battery string. Comparing with mean difference algorithm, FLC can improve the equalization speed, reduce the temperature rise and control the energy consumption better.

The proposed method has some limitations. For example, it’s necessary to measure the voltage and calculate the SOC of each cell which will cause the cost increasing. Besides, one FLC is used to control one cell’s equalization and the equalization controller will become very complex when applied in the battery pack with lots of batteries. In the future, a new equalization method based on FLC with less inputs for battery pack will be studied. Finally, the presented method will be used in electrical vehicle.

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