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Dual-Layer Inductor Active Equalization Control for Series-Connected Lithium-Ion Batteries Based on SOC Estimation

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Abstract: In order to reduce the time and improve the balancing speed of traditional single-layer inductive equalization circuits, this paper proposes an active equalization control strategy with double-layer inductors for series-connected battery packs, based on an accurate state-of-charge (SOC) estimation. By selecting the inductor as the intermediate energy storage element, the SOC of the single lithium-ion battery (LIB) cell is calculated by using a particle filter (PF) algorithm. Meanwhile, according to the deviation in SOC among the batteries, stop parameters are introduced to achieve the design and optimization of the equalization strategy. Finally, the relationship between the equalization current and the control signal period is derived to fulfill the equalization. The experimental results show that, compared with the traditional single-layer inductive equalization topology, the proposed equalization control topology can shorten the equalization time by at least 15.6%. More importantly, this equalization scheme overcomes the disadvantage of the long energy transfer path of traditional inductive equalization, which helps to improve the equalization speed and the inconsistency of the battery pack.

Keywords: automotive engineering; series-connected lithium batteries; active equalization; SOC; dual-layer inductor

1. Introduction

Currently, automotive industries are moving towards electrification, intelligence, networking and lightweight development. Electric vehicles (EVs) have been significantly developed to track this prospective trend, as they are energy saving and almost zero emission. As the main energy supplier of EVs, the lithium-ion battery (LIB) has been widely used in electric vehicles, due to its inherent performance, such as high energy density, long cycle life and low self-discharge rate, etc. However, the voltage of a single battery is too low to meet the voltage requirements for a real-driving EV; thus, the LIB pack is needed to meet the high voltage requirements of EVs, and it is necessary to connect multiple batteries in series. However, there is an inconsistency in the battery pack because of the difference in manufacturing processes and application conditions, which greatly limits the capacity, power and life of the battery pack, and may even cause safety issues [1–5]. In order to reduce the inconsistency of LIBs, it is necessary to design an appropriate active equalization circuit and the related control scheme to fulfill the consistency of each cell in the battery pack.

The equalization circuit is mainly divided into passive equalization and active equalization [6]. Although the circuit structure of passive equalization is simple and easy to control, it has the disadvantages of large energy loss and low efficiency [7]. In contrast, the active equalization circuit has become a research hotspot, in which inductance, capacitance, and converter are used as energy transmission media to achieve equalization [8–12]. Capacitive balance is mainly fulfilled through the voltage difference between batteries, and
it uses the capacitor as an energy storage element to realize capacity balance [13,14]. A series-parallel switched-capacitor equalization circuit is proposed in [15]. Although the circuit can maintain a faster equalization speed, each energy storage component needs to be equipped with four switches and one capacitor, which may greatly increase the volume and cost of the equalization circuit. In addition, the LC-type (inductance and capacitance) equalization circuit can realize equalization control through an LC oscillation circuit [16–20], and can effectively solve the problem concerning the small voltage difference. Unfortunately, the equalization speed and efficiency of the LC-type circuit will be greatly reduced, due to the switching frequency in the equalization circuit. For transformer-type equalization, the principle of the transformer is used to construct the equalization circuit, to realize the conversion of electric energy and magnetic energy. Compared with other equalization circuits, this balance circuit has a complicated structure, and the balance efficiency and speed are limited [21].

Different from the above equalization methods, the inductive equalization circuit that uses inductance as an intermediate energy storage element for energy transmission has the characteristics of easy control of the equalization current, a simple control principle, and easy implementation. Therefore, recently, it has gradually become a hotspot in the research of active equalization methods. In Ref. [22], an active equalization circuit, based on inductance, was proposed to realize the consistency among the battery pack; its control principle is similar to that of a switched capacitor equalization circuit, and the control principle is simple and easy to implement. In Ref. [23], a single-layer inductor active equalization circuit was presented to realize the energy transfer between two adjacent batteries, by controlling the on-off switch, and the inconsistency of different battery packs was effectively improved. A class of centralized active balancing circuits, based on multiple switches, was proposed in Ref. [24], and the required balancing cells were selected through the switch matrix for balancing. However, these equalization circuits can only realize the energy transfer within the battery pack, which might greatly increase the equalization time. To shorten the equalization time, a coupled inductance equalization circuit was presented in Ref. [25], yet the circuit cannot realize the energy transfer between the battery packs. Furthermore, it was only applicable for the situation in which the number of cells was even. To tackle the above issues, this paper proposes a double-layer inductor active equalization scheme to fulfill the active balancing of intra-group batteries and different batteries between the battery packs, improving the equalization speed.

The rest of this paper is organized as follows. Section 2 introduces the topology of energy transfer within and between the packs, based on the dual-layer inductor active equalization circuit and its working principle. In Section 3, the control strategy based on the state-of-charge (SOC) estimation is described. In Section 4, the equilibrium topology and its control strategy are verified by means of a simulation investigation conducted in MATLAB/Simulink software. Finally, the main contribution and further research direction of this paper are given in Section 5.

2. Materials and Methods
2.1. Double-Layer Inductive Equalization Circuit

In this section, the energy transfer topology of the dual-layer inductor active equalization circuit is adopted to derive our expected active equalization control scheme, as shown in Figure 1, in which eight battery cells are connected in series [26]. The balanced switches of $M_{11}$, $M_{12}$, ..., $M_{n1}$, $M_{n2}$ in the control group are connected to the first-layer inductances of $L_{11}$, $L_{21}$, ..., $L_{i1}$, $L_{ni}$, and the switches of $M_1$, $M_2$, ..., $M_i$, $M_n$ that control the balance between the groups are connected to the second-layer inductance $L_1$. When the equalization circuit is turned on, the individual cells in each series’ battery pack will be balanced in the first place, and when the balance within the group is completed, the equalization between the series-connected battery groups will be carried out until the end of the balance.
Before the equalization circuit works, the main values of each battery are collected by the controller; on this basis, the particle filter (PF) is used to estimate the SOC value of each cell, and then the opening and closing of each switch connected to the inductor are adjusted by comparing whether it reaches the equilibrium starting threshold.

2.2. Working Principle of the Equalization Circuit

According to Figure 1, this section takes four LIB cells in series as the research object to explain the detailed equalizing process of the circuit. The designed equalization circuit is shown in Figure 2, and the structure of the equalization module is shown in Figure 2a. When the circuit starts to work, energy is mainly transferred between the two layers of the equalization circuit, within and between groups. For in-group equalization, a closed circuit is composed of batteries Cell-1 and Cell-2, switches $M_{11}$ and $M_{12}$, diodes $D_{11}$ and $D_{12}$, inductor $L_{11}$, and resistor $R_{11}$, and another closed circuit is composed of batteries Cell-1 and Cell-2, switches $M_{11}$ and $M_{12}$, diodes $D_{11}$ and $D_{12}$, inductor $L_{11}$, and resistor $R_{11}$. The inter-group equalization mainly performs energy transfer between the closed equalization loop, containing two adjacent intra-group equalization circuits, and the equalization module, which is shown in Figure 2b.

![Figure 1. Double-layer inductance balance circuit scheme.](image-url)
By controlling the opening and closing of the MOSFET corresponding to a battery or battery pack with a higher SOC, energy can be transferred from a battery or battery pack with a higher SOC to a nearby battery or battery pack with a lower SOC. It is assumed that $\text{SOC}_{\text{Cell-1}} > \text{SOC}_{\text{Cell-2}}$ and $\text{SOC}_{\text{Cell-3}} > \text{SOC}_{\text{Cell-4}}$ for a single cell and $\text{SOC}_{\text{Pack-1}} > \text{SOC}_{\text{Pack-2}}$ for a battery pack. The circuit is firstly equalized within the group, that is to say, energy is transferred from high-energy Cell-1 and Cell-3 to low-energy Cell-2 and Cell-4 through inductors $L_{11}$ and $L_{21}$. When the circuit in the group reaches equilibrium, the equalization between groups is carried out. Meanwhile, energy will be transferred from the first group of batteries, with high energy, to the second group of batteries, with low energy, via $L_1$, until equilibrium is reached. The equalization process can be divided into the following three stages: discharging the battery or battery pack with a higher SOC, charging the battery or battery pack with a lower SOC, and demagnetizing the inductance. The specific working process is revealed in Figure 3.
In Figure 3, the first group is used to demonstrate the principle of the balance within the group. The equalization process can be divided into the following three steps:

1. Discharging the battery with a higher SOC in the group: Figure 3a shows a schematic diagram of the discharge process for the battery with a higher SOC in the group. Because SOC_{Cell-1} > SOC_{Cell-2}, M11 is turned on, and the discharge circuit is formed by Cell-1, L_{11}, R_{11} and M_{11}. The energy in Cell-1 will be released to L_{11}. It is worth noting that the discharge current flows in the same direction as the red arrow.

2. Charging the battery with a lower SOC in the group: The charge process of the battery with a lower SOC in the group is shown in Figure 3b. M_{12} is turned off, and Cell-2, L_{11}, and D_{12} form the charge circuit. The energy in L_{11} will be released to Cell-2. The charge current follows the green arrow.

3. Degaussing in the group: Figure 3c shows a schematic diagram of energy dissipation during the degaussing phase of the batteries in the group. After charging, the inductor needs to be magnetically reset. M_{11} is turned on; at this time, the degaussing circuit is made up of Cell-1, L_{11}, R_{11} and M_{11}, which consumes the remaining energy in L_{11} and prevents magnetic saturation.

After the single cells in the two groups are balanced, balancing between the two battery groups will be performed, as shown in Figure 4. The process of balancing between the groups is as follows:

4. Discharging the battery pack with a higher SOC between groups: The discharge process of the battery pack with a higher SOC between groups can be observed in Figure 4a. Because SOC_{pack-1} > SOC_{pack-2}, the balance control system will send a control signal to drive M_{1} to turn on. At this time, Pack-1, L_{1} and R_{1} form a discharge loop. The first group discharges and releases the energy to L_{1}. Conversely, the discharge current flows in the same direction as the red arrow.

5. Charging the battery packs with a lower SOC between groups: The charge process of the battery group with a lower SOC between the groups is shown in Figure 4b. M_{1} is turned off and D_{2} is turned on; at this time, L_{1}, D_{2} and Pack-2 form a charge circuit. L_{1} converts the magnetic energy into electrical energy and releases the energy to the second group. The charge current follows the green arrow.

6. Degaussing between the two groups: Figure 4c shows a schematic diagram of degaussing between the groups. M_{1} is turned on; L_{1}, R_{1} and the first group form the...
2.3. SOC Estimation Based on PF Algorithm

Based on the working principle of the above equalization circuit, the design of the equalization strategy can be divided into the following two steps: when \( \text{SOC}_i - \text{SOC}_n \geq 0.05 \) \((i = 1, 2, \ldots, n = 1, 2, \ldots)\), the balance is turned on, and when \( \text{SOC}_i - \text{SOC}_n \leq 0.01 \), the balance is turned off. The key to the balancing strategy based on the deviation in SOC is understanding how to accurately obtain the SOC of a single battery. As we all know, the PF algorithm is an effective way to predict the SOC, and has been widely used in [27–29]. More importantly, its accuracy and robustness have been widely validated in [30]. Therefore, this paper uses a PF to estimate the SOC of the battery, and the structure diagram of using a PF to predict the battery SOC is shown in Figure 5.

![Figure 5. Structure diagram of PF.](image)

According to Figure 5, this algorithm randomly selects some particles from the initial density distribution function for initialization, and estimates the mean value of the sample through the probability density function. Then, the weight of each particle is updated, according to the estimated result, and the dynamic parameters are predicted.

To further assess the feasibility of PF-based SOC estimation in this paper, the NCR18650B cell is measured with the ITS5300 battery testing system, as shown in Figure 6. It needs to be emphasized that the parameters of the battery model are obtained by hybrid pulse power characteristic (HPPC) test data.

According to the PF-based SOC estimation principle, the accuracy of the PF algorithm for battery SOC estimation is verified under urban dynamometer driving schedule (UDDS) conditions. The SOC estimation curve and its error, based on the PF algorithm, are shown in Figure 7.
3. Active Balancing Control Strategy for Series-Connected LIBs

The double-layer inductance active balance control strategy is proposed to control the opening and closing of the MOSFET corresponding to the battery with a higher SOC, and transfers energy from a battery with a higher SOC to a battery with a lower SOC. Thus, the relationship between the on–off state of the switch and the energy transmission can be obtained. For example, when SOC_{Cell-1} > SOC_{Cell-2}, M_{11} is closed. The charging loop shown in Figure 3a is a first-order RL circuit, and its zero-state response equation is as follows:

\[ V_1 = R_{on}i_L + L \frac{di}{dt}, t = 0 \to t_{on} \]  

(1)

where \( R_{on} \) is the total resistance in the circuit, \( P_1 \) is the control signal of \( M_{11} \), and the voltages of Cell-1 and Cell-2 are \( V_1 \) and \( V_2 \), respectively.

When \( M_{11} \) is turned on, \( L \) is the inductor value of \( L_{11} \), \( i_L \) is the current, and \( t_{on} \) is the closing time of \( M_{11} \). Equation (1) is a first-order differential equation with constant coefficients, and its general solution is as follows:

\[ i_L = \frac{V_1}{R_{on}} - \frac{V_1}{R_{on}} e^{-t_{on} \frac{R_{on}}{L}} = \frac{V_1}{R_{on}} \left( 1 - e^{-t_{on} \frac{R_{on}}{L}} \right), \]  

(2)
When the SOC difference between the two batteries reaches the starting threshold, the equation is as follows:

\[ \text{SOC}_{\text{cell}} - 1 - \text{SOC}_{\text{cell}} - 2 \geq 0.05 \]  

(3)

At this time, \( M_{11} \) is turned on, \( t = t_{\text{on}} \), the current in the circuit reaches the maximum value, and the maximum value is denoted as follows:

\[ i_{\text{max}} = \frac{V_{1}}{R_{\text{on}}} \left( 1 - e^{-\frac{t_{\text{on}}}{L}} \right) \]  

(4)

When \( P_{1} \) is low, \( M_{11} \) is turned off. The current in the process of energy transfer is calculated by the following:

\[ i_{L} = i_{\text{peak}} e^{-\frac{(t-t_{\text{on}})}{R_{\text{off}}}} - \frac{V_{2} + V_{D_{11}}}{R_{\text{off}}} \left( 1 - e^{-\frac{(t-t_{\text{on}})}{L}} \right), \]

\[ t = t_{\text{on}} \rightarrow t_{\text{off}} \]  

(5)

where \( V_{D_{11}} \) is the turn-on voltage of \( D_{11} \), and \( R_{\text{off}} \) is the total resistance in the circuit when \( M_{12} \) is turned off.

As shown in Equations (4) and (5), when \( M_{11} \) is turned off, \( L_{11} \) is charged, and the closing time of switch \( M_{11} \) is related to the equalization current. On this basis, the balance control strategy of the entire equalization circuit is designed. The double-layer inductance active balance control block diagram is shown in Figure 8.

\[ \text{SOC}_{\text{dif-1}} = \text{SOC}_{i} - \text{SOC}_{n} \]

\[ (i = 1, 2, \cdots; n = 1, 2, \cdots; i \neq n) \]  

(6)

\[ \text{SOC}_{\text{dif-2}} = \text{SOC}_{\text{Pack-1}} - \text{SOC}_{\text{Pack-2}} \]  

(7)

Figure 8. Flowchart for the battery pack equalization strategy.

As shown in Equations (6) and (7), where \( \text{SOC}_{i} \) and \( \text{SOC}_{n} \) represent the SOC values of two different battery cells, respectively, \( \text{SOC}_{\text{dif-1}} \) refers to the SOC difference between two batteries and \( \text{SOC}_{\text{dif-2}} \) characterizes the difference between the battery packs.
Since the balance principles of the two layers are the same as each other, the equalization of the single batteries Cell-1 and Cell-2 are taken as an example to verify the balance control strategy. Remarkably, here, the maximum balance current of the balance system is set to 7 A. According to the relationship between the maximum current and the inductance value, we select the inductance value L to be 1H; the resistance of the MOSFET is set to 10mΩ and the line resistance is ignored. The voltage of Cell-2 is 3.2 V, which is considered to be unchanged during an equalization process. Substituting the above parameters into Equation (2), it can be found that the closing time of M₁₁ is 2.2 s and the duty ratio of the control signal is 50%.

In order to evaluate the rationality of the calculated parameters, as shown in Figure 9, the intra-group equalization circuit simulation model is built in MATLAB/Simulink. The parameters of this circuit are as follows: L₁₁ (1 H), R₁₁ (10 kΩ) and V₂ (3.2 V); the duty cycle is 50% and the control signal is the default parameter from Simulink. The curve of the control signal and current change over time is shown in Figure 10.

![Figure 9. The simulation model of the intra-group equalization circuit.](image)

![Figure 10. Control signal and current curve.](image)
It can be observed from Figure 10 that the maximum value of the equilibrium current is 6.9 A, and the range of current in the inductor is 0–7 A, which shows that the proposed equilibrium design in this article meets the requirements.

4. Results and Discussions

This section takes a battery pack consisting of eight LIB cells as the research object, and builds the designed double-layer active equalization circuit simulation model in MATLAB/Simulink. To shorten the equalization time and verify the equalization effect, the initial SOC values of each battery cell are orderly set as 50%, 45%, 60%, 55%, 70%, 48%, 68% and 65%. Simultaneously, we compared the performance of the proposed equalization circuit with the traditional equalization circuit, under different current conditions. The equalization model consists of the battery module, double-layer inductor and switch control module. In addition, the parameters of the simulation model are as follows: L (1 H) and R (10 kΩ); the duty cycle is 50% and the diode D is the default parameter from Simulink. It should be noted that the equalization simulation in this paper is carried out without considering the influence of temperature and aging propagation on the estimation accuracy of the cells.

4.1. Equalization in the Static Condition

In order to illustrate the superiority of the proposed method, this paper builds the single-layer inductance active equalization circuit described in the literature [23] and the simulation model of the double-layer inductance equalization circuit proposed in this article, respectively, and compares their equilibrium performance under static conditions. The SOC change curves of each single battery for the two schemes are shown in Figure 11.

Figure 11. Static state simulation results of the two schemes.
It can be observed from Figure 11 that, under static conditions, although both equalization methods can eventually eliminate inconsistencies in the cells, the single-layer inductance active equalization circuit needs 5001 s to complete the equalization process, while the proposed double-layer inductance active equalization circuit only needs 3172 s. In comparison, the proposed double-layer inductance can shorten the equalization time by 36.6%. In addition, as shown in Figure 11, the equalization scheme in [23] achieves equalization by transferring energy between adjacent batteries. The equalization path is long and the equalization time is slow. However, the proposed double-layer inductor is actively equalized. The plan is to modularize the series’ battery pack, which shortens the equalization path, to a certain extent, and the equalization speed is significantly accelerated.

4.2. Charge and Discharge Equalization

To further verify the performance of the proposed double-layer inductance active equalization circuit, under the same simulation conditions as in Section 4.1, it is compared with the single-layer inductance active equalization circuit in [23], under different charge and discharge rates; Figures 12 and 13 indicate the particular variations in SOC values of each monomer, respectively.

As shown in Figures 12 and 13, under the same initial SOC value, no matter what the charge or discharge rate is, the equalization time of the proposed double-layer inductance active equalization circuit is less than the single-layer inductance equalization circuit. Combined with the simulation results of static equalization and charge–discharge equalization, it can be verified that the proposed double-layer inductance active equalization circuit has the advantage of dynamic adjustment of the equalizing current.

Figure 12. Different charging rate state simulation results.
4.3. Performance Comparison of Active Balancing Strategies under Dynamic UDDS Condition

In order to compare and analyze the performance of the proposed active balancing strategy under dynamic UDDS conditions, the initial SOC value of each single battery remains unchanged and the simulation time is set to 2000 s. After the simulation is performed, the battery equalization results under UDDS conditions are shown in Figure 14.

As can be observed from Figure 14, it takes 1538 s and 1298 s for the two circuits to complete equalization under UDDS conditions, separately. However, compared with the single-layer inductance equalization circuit, the double-layer inductance equalization circuit obtains a better equalization efficiency, and its equalization time is reduced by 240 s. To this end, the equalization speed of the proposed double-layer inductance active equalization circuit is faster than the single-layer inductance active equalization circuit proposed in [23], and it has good applicability under dynamic conditions.

For a better quantitative analysis of the proposed methods, the performance comparison of the two equalization schemes is listed in Table 1. It can be observed from Table 1 that the result verifies the advantages of the proposed equalization scheme, which can greatly shorten the equalization time.
This paper presents an active balancing control scheme for the double-layer inductance of the series’ battery pack, based on the SOC estimation, to reduce the inconsistency between the individual cells used in the series-connected power battery pack of EVs. Firstly, the overall scheme of the double-layer inductance active equalization circuit is constructed by combining the principle of the inductance equalization circuit and the layering idea, which not only realizes the balance between the individual cells in the series’ battery packs, but also achieves balance among the series-connected battery packs. Secondly, according to the overall idea of the circuit design and the characteristics of each equilibrium index, SOC is selected as the equilibrium evaluation index. The SOC estimation framework is constructed in combination with the PF algorithm, and the estimation accuracy of the algorithm is verified under UDDS conditions, and its estimation error is kept within 4%. Finally, the balancing strategy design is carried out for the modules of the series’ battery pack.
pack and between the modules, to control the on–off frequency of the MOSFET with the balance current, and then the balance time of the entire circuit is controlled. Taking a battery pack consisting of eight LIB cells as the research object, the simulations of the equalization process of the battery pack are performed in the static state, the charging state, and the discharging state. The simulation results showed that the proposed double-layer inductance active equalization circuit could achieve fast equalization. Compared with the equilibrium scheme in [23], the proposed equalization scheme has obvious advantages, in terms of equalization speed and equalization time. The follow-up research will carry out experimental verification of the equilibrium control. Moreover, we will construct two battery model types, considering the influence of temperature and aging propagation, to reduce the impact of the SOC estimation accuracy on the equalization performance.

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