Research on a Novel Power Inductor-Based Bidirectional Lossless Equalization Circuit for Series-Connected Battery Packs

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Abstract: Cell balancing plays an important role in preserving the life of series-connected battery packs; without a suitable balancing system, the individual cell voltages will differ over time, and the battery pack capacity will decrease quickly. This paper presents a novel power inductor-based bidirectional lossless equalization circuit. This circuit consists of several balancing sub-circuits, which allow the dynamic adjustment of the equalization path and equalization threshold. The simulation and experiment results demonstrate that the proposed circuit, which features a simple control method, fast balancing, and a large equalization current, exhibits outstanding equalization performance.

Keywords: series-connected battery pack; bidirectional lossless equalization; power inductor

1. Introduction

Power batteries require a variety of series or parallel combinations to achieve the voltages or capacities required for various applications. This paper focuses on lithium-ion (Li-ion) battery cells
because of their great potential for future vehicle applications [1]. Due to the inhomogeneity among individual cells, subjecting a power battery group to several charging or discharging cycles can cause some of the cells to overcharge or overdischarge during use, which can degrade the group performance, shorten its lifetime, and even pose a safety hazard. To prolong the battery group lifetime, power battery equalization must be realized [2–7].

Depending on the energy transfer mode, equalization circuits can be divided into two types: balancing circuits, which include energy dissipation, and other circuits without energy dissipation [8]. Although several topological structures exist for the latter type, almost all of them use energy storage elements and balancing bypass to build the energy transport channels and directly or indirectly transfer the energy from the high-energy cell to the lower-energy cell or cells. These latter circuits can generally be categorized as either capacitance, converter or transformer circuits, each of which has its own advantages and disadvantages in terms of accuracy, cost, and efficiency. Uno [2], Kim [3], Kobzev [9] and others have proposed several equalization circuit topologies based on switch capacitance, which charges or discharges capacitors to realize energy transfer. However, these circuits suffer from a longer balancing time, especially in cases with a small difference in battery voltage. Converter-type equalization circuits use power inductors for energy transfer and are based on buck, boost or Ćuk converters. The equalization circuits proposed by Lee [4], Yarlagadda [5], Kim [10], Lu [11], Chen [12], and Hou [13] belong to this type. Converter equalization circuits can realize bidirectional energy flow and offer higher balancing efficiency, but often require a complex switch array and a precise control algorithm. Finally, transformer-type equalization circuits have the basic structure of a fly-back transformer [14–17], which can be divided into a variety of types, such as single magnetic cores, multiple magnetic cores, single vice sides, and multiple vice sides. Transformer-type equalization circuits have a high level of integration and high balancing speed but poor expandability and large transformer magnetic flux leakage.

Considering the advantages and disadvantages of the power battery equalization circuits discussed above, this paper proposes a novel power inductor-based equalization circuit with the advantages of a simple structure, a simple control algorithm and high efficiency. The main idea of the equalization circuit is to reduce the charging current of the single cell with a higher terminal voltage and then prevent overcharge during charging by controlling the balancing sub-circuits. During discharge, the proposed equalization circuit can reduce the discharging current of the low-voltage single cell and then prevent over-discharge by controlling the balancing sub-circuits. In the suspended state, the equalization circuit can realize cell discharging with high energy and cell charging with low energy.

The remainder of this paper is organized as follows: in Section 2, the structure and principle of equalization circuits are described. In Section 3, the fundamental parameters of the equalization circuit are calculated. The simulation framework is introduced in Section 4. The experimental verifications are presented in Section 5. Finally, conclusions are given in Section 6.

2. Equalization Circuit Structure and Principles

In this section, the equalization circuit structure and principles are described. The equalization principles include the single-cell equalization principle and two fluctuating battery parts equalization principle.
2.1. Equalization Circuit Structure

The equalization circuit diagram is shown in Figure 1, where Figure 1a is the equalization circuit schematic diagram and Figure 1b is the balancing sub-circuit principle diagram. A battery pack with cutoff point K is divided into two parts. The total number of cells can be odd or even. If n is an even number, \( n = 2 \times k \); if n is an odd number, \( n = 2 \times k - 1 \).

![Equalization circuit diagram](image)

**Figure 1.** Equalization circuit. (a) Equalization circuit scheme; (b) Balancing sub-circuit scheme.

In this process, the battery pack has four different working conditions: charging, discharging, the suspended state after charging, and the suspended state after discharging. Among these working conditions, the equalization principles of the charging state and the suspended state after charging are consistent, and the equalization principle of the discharging state is the same as that of the suspended state after discharging. The novelty of the proposed circuit is in the dynamic adjustment of the equalization path and of the equalization threshold, described as follows:
(1) Dynamic adjustment of the equalization path. During equalization, the balancing sub-circuit $S$ is responsible for the equalization path of the two parts of the battery pack, and the balancing sub-circuit $S_i$ controls the equalization path of single cell $B_i$.

(2) Dynamic adjustment of the equalization threshold. The equalization circuit has two equalization thresholds; one for the individual cells and one for the two fluctuation parts. If the two equalization thresholds are not met, the equalization circuit stops working.

The balancing sub-circuit $S$ is responsible for balancing the two parts of the battery pack, and its working condition is:

$$\left| \frac{V_1 + V_2 + \ldots + V_k}{k} - \frac{V_{k+1} + V_{k+2} + \ldots + V_n}{n-k} \right| > 5 \text{mV}$$  \hspace{1cm} (1)

Each cell $B_i$ is equipped with a balancing sub-circuit $S_i$ that controls the equalization of the single cell $B_i$. During charging or within the suspended state after charging, the working condition of $S_i$ is $V_i = V_{\text{max}} > V_{\text{avg}} + 10 \text{ mV}$; $i = 1,2,\ldots,n$; $V_{\text{avg}} = (V_1 + V_2 + \ldots + V_n)/n$. Meanwhile, during discharging or within the suspended state after discharging, the working condition of $S_i$ is $V_i = V_{\text{min}} < V_{\text{avg}} - 10 \text{ mV}$.

Cell balancing based on voltage uniformity is more easily implemented and more common [18]. In this paper, the single-cell terminal voltage serves as the index of inconsistency.

2.2. Equalization Principle

This paper uses four cells in a series battery pack as an example to elaborate the circuit equalization principle. The equalization circuit is shown in Figure 2. If the inconsistency between single cell $B_i$ and the other cells satisfies the equalization conditions, balancing sub-circuit $S_i$ works. If the two fluctuation parts satisfy the working conditions of balancing sub-circuit $S_i$, circuit $S$ works. Finally, the equalization process is over when neither $S_i$ nor $S$ works.

![Figure 2. Equalization circuit of four series-connected cells.](image-url)
2.2.1. Single-Cell Equalization Principle

(1) Equalization principles for the charging process or the suspended state after charging

The equalization principles of the charging state and suspended state after charging are consistent and involve realizing the equalization by first identifying the higher cell voltage and then controlling the corresponding balancing sub-circuits $S_i$ and $S$. Suppose that the cell voltage of $B_1$ is higher than that of the other cells during charging or in the suspended state after charging. The equalization principle can then be divided into the following two main stages:

Stage 1: $L_1$ charges.

Figure 3 presents a schematic of the equalization principle assuming that the voltage of cell $B_1$ is higher than that of the other cells during charging or in the suspended state after charging. By closing switch $S_{1a}$, cell $B_1$ charges inductor $L_1$, and $L_1$ stores energy. The current $i_L$ gradually increases, and some of the electrical energy transfers into magnetic energy stored in the inductor. The closing time $t_{on}$ of switch $S_{1a}$ determines the maximum $I_{max}$ of inductor current $i_L$:

\[
V_{bs} = R_{on}i_L + L \frac{di}{dt} \quad 0 < t \leq t_{on}
\]

where, $R_{on}$ is the circuit total resistance when closing switch $S_{1a}$, including the PCB line resistance, the DC resistance of inductor $L_1$, and the turn-on resistance of switch $S_{1a}$. $L$ represents the $L_1$ inductance, $i_L$ is the current flowing in the inductor, and $t_{on}$ is the closing time of switch $S_{1a}$.

A general solution of Equation (2) is:

\[
i_L = \frac{V_{bs}}{R_{on}} - \frac{V_{bs}}{R_{on}} e^{-\frac{R_{on}}{L}} = \frac{V_{bs}}{R_{on}} (1 - e^{-\frac{R_{on}}{L}}) \quad 0 < t \leq t_{on}
\]

If $t = t_{on}$, the circuit current reaches its maximum value; that is:

\[
i_L = i_p = \frac{V_{bs}}{R_{on}} (1 - e^{-\frac{R_{on}}{L}}) \quad t = t_{on}
\]
In this process, inductor $L_1$ stores energy, and balancing sub-circuit $S_1$ decreases the charging current of cell $B_1$ by absorbing it:

$$i_{B_1} = I_{ch} - i_{cl}$$

(5)

Stage 2: $L_1$ discharges.

Figure 4 presents a schematic of the $L_1$ discharge process. When $t > t_{on}$, switch $S_{1a}$ disconnects, and inductor $L_1$ charges the residual cells through the flywheel diode of switch $S_{1b}$ to realize the energy transfer from cell $B_1$ to the other cells. The circuit is the first-order full response, and its solution is:

$$i_L = i_0 e^{-\frac{t-t_{on}}{R_{off}} - \frac{V_D}{R_{off}} (1 - e^{-t/t_d})} - \frac{v_{B2} + v_{B3} + v_{B4}}{R_{off}}$$

$t_{on} < t \leq t_d$

(6)

where $V_D$ is the voltage drop of body diode $S_{1b}$; $R_{off}$ represents the total resistance of the discharge loop; $v_B$ is the total voltage drop of $B_2$, $B_3$, and $B_4$; and $t_d$ is the discharge period. Hence, the above formula can also be written as:

$$i_L = (i_0 + \frac{v_{B2} + v_{B3} + v_{B4}}{R_{off}}) e^{-\frac{t-t_{on}}{R_{off}}} - \frac{v_{B2} + v_{B3} + v_{B4}}{R_{off}}$$

$t_{on} < t \leq t_d$

(7)

After this process, inductor $L_1$ charges cells $B_2$, $B_3$ and $B_4$ through the body diode of MOSFET $S_{1b}$ to augment the charging currents of cells $B_2$, $B_3$ and $B_4$.

$$i_{B_2} = i_{B_3} = i_{B_4} = I_{ch} + i_{dl}$$

(8)

Figure 4. $L_1$ discharging schematic.

(2) Equalization principle for the discharging process or the suspended state after discharging

During discharging or in the suspended state after discharging, the equalization principle can be similarly divided into the following two stages. In the following, suppose the voltage of cell $B_3$ is lower than that of the other cells.
Stage 1: \(L_3\) charges.

Figure 5 presents a schematic of the \(L_3\) charging process. In this process, MOSFET \(S_{3a}\) is closed, cells \(B_1\) and \(B_2\) charge inductor \(L_3\), and inductor \(L_3\) stores the energy. Balancing sub-circuit \(S_3\) absorbs the currents of cells \(B_1\) and \(B_2\) to increase their discharging current:

\[
i_{b_1} = i_{b_2} = I_{\text{ds}} + i_3
\]  

(9)

![Figure 5. \(L_3\) charging schematic.](image)

Stage 2: \(L_3\) discharges.

Figure 6 presents a schematic of the \(L_3\) discharging process. In this process, MOSFET \(S_{3a}\) disconnects, and inductor \(L_3\) charges cell \(B_3\) by the body diode of MOSFET \(S_{3b}\) to decrease the discharging current of cell \(B_3\):

\[
i_{b_3} = I_{\text{ds}} - i_{B_3}
\]  

(10)

![Figure 6. \(L_3\) discharging schematic.](image)
2.2.2. Equalization Principle for the Two Fluctuating Battery Parts

In the example of four single cells, suppose that the voltage in the upper half of the battery pack is greater than that in the lower half during charging or in the suspended state after charging and that the voltage values satisfy the working conditions of balancing sub-circuit \( S \). Hence, the upper half of the battery requires discharge equalization, and the equalization process is divided into two stages as shown in Figure 7.

As shown in Figure 7a, when switch \( S_a \) is turned on, cells \( B_1 \) and \( B_2 \) charge inductor \( L \). Then, as shown in Figure 7b, when switch \( S_a \) is disconnected, inductor \( L \) charges cells \( B_3 \) and \( B_4 \) by the body diode of \( S_b \). Finally, the energy transfer from \( B_1 \) and \( B_2 \) to \( B_3 \) and \( B_4 \) is achieved.

Suppose that the voltage in the upper half of the battery pack is smaller than that in the lower half during discharging or in the suspended state after discharging and that the voltage values satisfy the working conditions of balancing sub-circuit \( S \). The upper half then requires charging equalization, and the equalization process can be divided into two stages, as shown in Figure 8.

![Figure 7](image1)

**Figure 7.** Working process of \( L \). (a) \( L \) charging process; (b) \( L \) discharging process.

![Figure 8](image2)

**Figure 8.** Working process of \( L \). (a) \( L \) charging process; (b) \( L \) discharging process.
As shown in Figure 8a, when switch $S_{b}$ is turned on, cells $B_3$ and $B_4$ charge inductor $L$. Then, as shown in Figure 8b, when switch $S_{b}$ is disconnected, inductor $L$ charges cells $B_1$ and $B_2$ by the body diode of $S_a$. Finally, the energy transfer from $B_3$ and $B_4$ to $B_1$ and $B_2$ is achieved.

3. Calculation of the Equalization Circuit Parameters

In this section, the fundamental parameters of the equalization circuit are calculated, including those for the charging process and the suspended state after charging and those for the discharging process and the suspended state after discharging.

3.1. Calculation of the Equalization Circuit Parameters for the Charging Process and the Suspended State after Charging

The resistance $R_{on}$ in the equalization circuit is usually ignored during charging and in the suspended state after charging; when $i \leq k$ and the voltage of cell $B_i$ is higher than that of the other cells, the control circuit manipulates balancing sub-circuit $S_i$ to realize the discharge equalization of cell $B_i$.

The current passing through inductor $L_i$ increases linearly when MOSFET $S_{ia}$ is turned on. Meanwhile, inductor $L_i$ stores the energy transmitted from cell $B_i$:

$$i_{Li} = \frac{V_i \cdot t}{L} \quad (0 < t < D \cdot T) \quad (11)$$

where $T$ represents the switching cycle, $D$ represents the duty cycle, $t$ represents the time, $i_{Li}$ represents the inductor current of $L_i$, $V_i$ represents the voltage of cell $B_i$, and $L$ represents the inductance value of $L_i$.

The current passing through inductor $L_i$ decreases linearly when MOSFET $S_{ia}$ is turned off. Meanwhile, the inductor charges cells $B_{i+1}, B_{i+2}, \ldots, B_{n-1}, B_n$:

$$i_{Li} = I_p = \sum_{j=i+1}^{n} \frac{V_j \cdot t}{L} \quad (D \cdot T < t < T) \quad (12)$$

$$I_p = \frac{V_i \cdot D \cdot T}{L} \quad (13)$$

where $I_p$ represents the peak current passing through inductor $L_i$ and $V_j$ represents the voltage of cell $B_j$.

The average charging current of cell $B_i$ in balancing sub-circuit $S_i$ decreases by $I_{id}$ in one period:

$$I_{id} = \frac{I_p \cdot D \cdot T}{2} = \frac{V_i \cdot D^2 \cdot T}{2L} \quad (14)$$

The average charging current of cells $B_{i+1}, B_{i+2}, \ldots, B_{n-1}, B_n$ in balancing sub-circuit $S_i$ increases by $I_{ioc}$ in one period:

$$I_{ioc} = \frac{1}{T} \cdot \frac{I_p \cdot T_i}{2} = \frac{V_i \cdot D \cdot T_i}{2L} \quad (15)$$

where $T_i$ represents the time required for the current in the inductor to decrease from its maximum to zero.
When \( i > k \), the control circuit accomplishes the discharge equalization of cell \( B_i \) by activating MOSFET \( S_{ib} \) in balancing sub-circuit \( S_i \).

The current passing through inductor \( L_i \) increases linearly when MOSFET \( S_{ib} \) is turned on. Meanwhile, inductor \( L_i \) stores the energy transmitted from cell \( B_i \):

\[
i_{Li} = \frac{V_i \cdot t}{L} \quad (0 < t < D \cdot T)
\] (16)

The current passing through inductor \( L_i \) decreases linearly when MOSFET \( S_{ib} \) is turned off. Meanwhile, the inductor charges cells \( B_1, B_2, \ldots, B_{i-1} \):

\[
i_{Li} = I_p \cdot \frac{\sum_{j=1}^{i} V_j \cdot t}{L} \quad (D \cdot T < t < T)
\] (17)

The average charging current of cell \( B_i \) in balancing sub-circuit \( S_i \) decreases by \( I_{id} \) in one period:

\[
I_{id} = \frac{1}{T} \cdot \frac{I_p \cdot D \cdot T}{2} = \frac{V_i \cdot D^2 \cdot T}{2L}
\] (18)

The average charging current of cells \( B_1, B_2, \ldots, B_{i-2}, B_{i-1} \) in balancing sub-circuit \( S_i \) increases by \( I_{soc} \) in one period:

\[
I_{soc} = \frac{1}{T} \cdot \frac{I_p \cdot T_i}{2} = \frac{V_i \cdot D \cdot T_i}{2L}
\] (19)

where \( T_i \) represents the time required for the current in the inductor to decrease from its maximum to zero.

To ensure that the current passing through the inductor can return to zero within one period, \( T_i + D \cdot T \leq T \) must be satisfied. The current in the inductor is in the discontinuous current mode (DCM) if \( T_i + D \cdot T < T \) and the critical continuous current mode (CCM) if \( T_i + D \cdot T = T \). Because the method for the parameter calculation for balancing sub-circuit \( S \) is the same as that for balancing sub-circuit \( S_i \), it is omitted here.

### 3.2. Calculation of the Equalization Circuit Parameters for the Discharging Process and the Suspended State after Discharging

The resistance \( R_{on} \) in the equalization circuit is usually ignored within the discharge state. When \( i \leq k \), the control circuit manipulates balancing sub-circuit \( S_i \) to realize the charging equalization of cell \( B_i \).

The current passing through inductor \( L_i \) increases linearly when MOSFET \( S_{ib} \) is turned on. Meanwhile, inductor \( L_i \) stores the energy transmitted from cells \( B_{i+1}, B_{i+2}, \ldots, B_{n-1}, B_n \):

\[
i_{Li} = \frac{\sum_{j=i+1}^{n} V_j \cdot t}{L} \quad (0 < t < D \cdot T)
\] (20)

The current passing through inductor \( L_i \) decreases linearly when MOSFET \( S_{ib} \) is turned off. Meanwhile, inductor \( L_i \) charges cell \( B_i \):
\[ i_L = I_p - \frac{V_i \cdot t}{L} \quad (D \cdot T < t < T) \] (21)

\[ I_p = \frac{\sum_{j=1}^{n} V_j \cdot D \cdot T}{L} \] (22)

where \( I_p \) represents the peak value of the current passing through inductor \( L_i \), \( V_i \) represents the voltage of cell \( B_i \), and \( V_j \) represents the voltage of cell \( B_j \).

\( I_{ic} \) represents the average charging current of cell \( B_i \) per period manipulated by balancing sub-circuit \( S_i \):

\[ I_{ic} = \frac{1}{T} \cdot \frac{I_p \cdot T_i}{2} = \frac{\sum_{j=1}^{n} V_j \cdot D \cdot T_i}{2L} \] (23)

where \( T_i \) represents the time required for the current in the inductor to decrease from its maximum to zero.

When \( i > k \), the control circuit accomplishes the charging equalization of cell \( B_i \) by activating MOSFET \( S_{ia} \) in balancing sub-circuit \( S_i \).

The current passing through inductor \( L_i \) increases linearly when MOSFET \( S_{ia} \) is turned on. Meanwhile, inductor \( L_i \) stores the energy transmitted from cells \( B_1, B_2, \ldots, B_{i-2}, B_{i-1} \):

\[ i_L = \frac{\sum_{j=1}^{i-1} V_j \cdot t}{L} \quad (0 < t < D \cdot T) \] (24)

The current passing through inductor \( L_i \) decreases linearly when MOSFET \( S_{ia} \) is turned off. Meanwhile, the inductor charges cells \( B_i \):

\[ i_L = I_p - \frac{V_i \cdot t}{L} \quad (D \cdot T < t < T) \] (25)

\[ I_p = \frac{\sum_{j=1}^{i-1} V_j \cdot D \cdot T}{L} \] (26)

where \( I_p \) represents the peak value of the current passing through inductor \( L_i \), and \( V_i \) represents the voltage of cell \( B_i \).

The average charging current value of cell \( B_i \) in balancing sub-circuit \( S_i \) increases by \( I_{ic} \) in one period:

\[ I_{ic} = \frac{1}{T} \cdot \frac{I_p \cdot T_i}{2} = \frac{\sum_{j=1}^{i-1} V_j \cdot D \cdot T_i}{2L} \] (27)

where \( T_i \) represents the time required for the current in the inductor to decrease from its maximum to zero.

To ensure that the current passing through the inductor can return to zero within one period, \( T_i + D \cdot T \leq T \) must be satisfied. The current in the inductor is in the DCM if \( T_i + D \cdot T < T \) and the critical CCM if \( T_i + D \cdot T = T \). Because the method for the parameter calculation of balancing sub-circuit \( S \) is the same as that for balancing sub-circuit \( S_i \), it is omitted here.
4. Simulation Framework

The PSIM software was employed in the simulation, and the switching frequency was set to 10 kHz. To reduce the time required for equalization, capacitors (1F), which were regarded as ideal elements, were used as substitutes for the cells. It was assumed that the MOSFET and inductors were all ideal elements as well. Moreover, the influence of parasitic inductance and parasitic capacitance and the deviation generated by AD transfer were ignored. The topology of the circuit is presented in Figure 9. The active condition set for balancing sub-circuit $S_i$ in the equalization control strategy during the charge process and in the suspended state after charging was $V_i = V_{\text{max}} > V_{\text{avg}} + 10 \text{ mV}$, $i = 1, 2, 3, 4$, $V_{\text{avg}} = (V_1 + V_2 + V_3 + V_4)/4$. The active condition set for balancing sub-circuit $S$ was $|| (V_1 + V_2) | - | (V_3 + V_4) || > 10 \text{ mV}$. The active condition set for balancing sub-circuit $S_i$ in the equalization control strategy during the discharge process and in the suspended state after discharging was $V_i = V_{\text{min}} < V_{\text{avg}} - 10 \text{ mV}$, $i = 1, 2, 3, 4$, $V_{\text{avg}} = (V_1 + V_2 + V_3 + V_4)/4$. The active condition set for balancing sub-circuit $S$ was $|| (V_1 + V_2) | - | (V_3 + V_4) || > 10 \text{ mV}$. Because the equalization principle of the charging state and the suspended state after charging are consistent, the equalization principle of the discharging state is the same as that of the suspended state after discharging. This section uses the suspended state after charging and the suspended state after discharging as examples. The equalization circuit topology is shown in Figure 9, and the equalization principles are validated as follows.

![Simulation circuit diagram](image_url)

**Figure 9.** Simulation circuit diagram.

4.1. Simulation of Suspended State after Charging

Figure 10 presents the program flowchart of equalization during charging or in the suspended state after charging.
When the battery pack is charging or in the suspended state after charging, the system will check the voltage of each cell to determine whether the working conditions of $S_i$ and $S$ are met. Balancing sub-circuit $S_i$ will function under the condition in which $V_i = V_{\text{max}} > V_{\text{avg}} + 10 \text{ mV}$, and balancing sub-circuit $S$ will function under the condition in which $|| (V_1 + V_2) - | (V_3 + V_4) || > 10 \text{ mV}$. The equalization will not stop unless neither the working condition for $S$ nor that for $S_i$ is achieved. In the simulation circuit topology shown in Figure 9, the voltage of cell $B_2$ is higher than those of the other cells. The simulation results are presented in Figure 11.

![Figure 10. Program flowchart of equalization during charging or in the suspended state after charging.](image)

Figure 10. Program flowchart of equalization during charging or in the suspended state after charging.

Figure 11 illustrates that, when the equalization circuit starts to work, the voltage of each cell meets the working conditions of $S$ and $S_2$; thus, balancing sub-circuits $S$ and $S_2$ start to work, and the transfer of energy from $B_2$ to $B_1$, $B_3$ and $B_4$ is realized. All single-cell voltages converge at approximately 0.078 s, after which $V_i < V_{\text{avg}} + 10 \text{ mV}$ and $|| (V_1 + V_2) - | (V_3 + V_4) || < 10 \text{ mV}$, the active conditions for $S$ or $S_i$ are not achieved, and the equalization goals are achieved.

![Figure 11. Terminal voltage of each cell.](image)

Figure 11. Terminal voltage of each cell.
4.2. Simulation of the Suspended State after Discharging

Figure 12 presents the program flowchart for equalization during discharging or in the suspended state after discharging.

When the battery pack is discharging or in the suspended state after discharging, the system will check the voltage of each cell to determine whether the working conditions of $S_i$ and $S$ are met. Balancing sub-circuit $S_i$ will function under the condition in which $V_i = V_{\text{min}} < V_{\text{avg}} - 10 \text{ mV}$, and balancing sub-circuit $S$ will function under the condition in which $|| (V_1 + V_2) - (V_3 + V_4) || > 10 \text{ mV}$. This equalization will not stop unless neither the working condition for $S$ nor that for $S_i$ is achieved. In the simulation of circuit topology shown in Figure 9, the voltage of cell $B_4$ is lower than those of the other cells. The simulation results are presented in Figure 13.

Figure 13 illustrates that, when the equalization circuit starts to work, the voltage of each cell meets the working conditions of $S$ and $S_4$. Thus, balancing sub-circuits $S$ and $S_4$ start to work, the transfer of energy from $B_2$ to $B_1$, $B_3$ and $B_4$ is realized, and the equalization will not stop unless neither the working condition for $S$ nor that for $S_i$ is achieved. As shown in the figure, all single-cell voltages converge at approximately 0.0049 s, after which $V_i > V_{\text{avg}} - 10 \text{ mV}$, $|| (V_1 + V_2) - (V_3 + V_4) || < 10 \text{ mV}$, the active conditions for $S$ or $S_i$ are not qualified, and the equalization goals are achieved.
Figure 13. Terminal voltage of each cell.

5. Experimental Verification

Based on the above analysis, to further verify the effectiveness of the equalization circuit, an experiment was conducted using four three Ah LiFePO$_4$ batteries, with inductances of 330 $\mu$H and a switching frequency of 10 kHz. Figure 14 shows the experimental circuit.

The role of the equalization circuit for the power battery was tested, including the charging process, the suspended state after charging, the discharging process, and the suspended state after discharging. To facilitate the analysis, the equalization current $I_{eq}$ was defined as the change in the average current of $B_i$ after the action of balancing sub-circuits $S_i$ and $S_j$; that is:
\[ I_{eq} = I_B(t) - I_B(0) \]  

(28)

5.1. Experimental Results for the Charging Process and the Suspended State after Charging

The power battery charging current was set as \( I_{ch} = 500 \) mA, and the initial voltages of the cells were as shown in Table 1.

**Table 1. Initial voltages of all cells for the charging process.**

<table>
<thead>
<tr>
<th>( V_1 )</th>
<th>( V_2 )</th>
<th>( V_3 )</th>
<th>( V_4 )</th>
<th>Working Switch</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.541</td>
<td>3.506</td>
<td>3.509</td>
<td>3.508</td>
<td>( S_1, S )</td>
</tr>
<tr>
<td>2.509</td>
<td>3.541</td>
<td>3.508</td>
<td>3.506</td>
<td>( S_2, S )</td>
</tr>
<tr>
<td>3.506</td>
<td>3.509</td>
<td>3.541</td>
<td>3.508</td>
<td>( S_3, S )</td>
</tr>
<tr>
<td>3.508</td>
<td>3.506</td>
<td>3.509</td>
<td>3.541</td>
<td>( S_4, S )</td>
</tr>
</tbody>
</table>

During charging, the average current values of \( B_i \) when balancing sub-circuits \( S_i \) and \( S \) were working are shown in Figure 15a. When voltage \( V_1 \) was larger than the other cell voltages, all single-cell voltages before and after the work of the balancing sub-circuits are shown in Figure 15b. Figure 15a shows that \( I_{eq1} = -297 \) mA, \( I_{eq2} = -290 \) mA, \( I_{eq3} = -295 \) mA, and \( I_{eq4} = -294 \) mA when the power battery pack was charging with a 500 mA current. The equalization current \( I_{eq} \) of the balancing sub-circuits reached up to 0.1 C. when sub-circuits \( S_i \) and \( S \) were working, they were able to reduce or even eliminate the charging current of the higher-voltage cell. Figure 15b shows that, after the work of the equalization circuit, all single-cell voltages converged.

![Figure 15. Cont.](image-url)
Figure 15. (a) Power battery pack charging current and single-cell currents; (b) Single-cell voltages before and after the work of the balancing sub-circuits.

In the suspended state after charging, the initial voltages of the four cells were as shown in Table 2.

Table 2. Initial voltages of all cells in the suspended state after charging.

<table>
<thead>
<tr>
<th>$V_1$</th>
<th>$V_2$</th>
<th>$V_3$</th>
<th>$V_4$</th>
<th>Working Switch</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.54</td>
<td>3.509</td>
<td>3.508</td>
<td>3.51</td>
<td>$S_1, S$</td>
</tr>
<tr>
<td>2.51</td>
<td>3.54</td>
<td>3.509</td>
<td>3.508</td>
<td>$S_2, S$</td>
</tr>
<tr>
<td>3.506</td>
<td>3.509</td>
<td>3.54</td>
<td>3.508</td>
<td>$S_3, S$</td>
</tr>
<tr>
<td>3.509</td>
<td>3.508</td>
<td>3.51</td>
<td>3.54</td>
<td>$S_4, S$</td>
</tr>
</tbody>
</table>

The average current values of $B_i$ when balancing sub-circuits $S_i$ and $S$ were working are shown in Figure 16a. When voltage $V_3$ was larger than the other cell voltages, all single-cell voltages before and after the work of the balancing sub-circuits are shown in Figure 16b.

Figure 16. Cont.
Figure 16. (a) Average current values of $B_i$ during the work of sub-circuits $S_i$ and $S$; (b) All single-cell voltages before and after the work of the balancing sub-circuits.

Figure 16a shows that $I_{eq1} = -301$ mA, $I_{eq2} = -300$ mA, $I_{eq3} = -300$ mA, $I_{eq4} = -298$ mA in the suspended state after charging. The equalization current $I_{eq}$ of the balancing sub-circuit reached up to 0.1 C. When sub-circuits $S_i$ and $S$ were working, they could transfer energy from the higher-energy cells to the lower-energy cells. Figure 16b shows that, after the operation of the equalization circuit, all single-cell voltages converged.

5.2. Experimental Results for the Discharging Process and the Suspended State after Discharging

The power battery discharging current was $I_{dis} = -500$ mA. During discharging, the initial voltages of the four cells were as shown in Table 3.

<table>
<thead>
<tr>
<th>$V_1$</th>
<th>$V_2$</th>
<th>$V_3$</th>
<th>$V_4$</th>
<th>Working Switch</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.84</td>
<td>2.924</td>
<td>2.921</td>
<td>2.923</td>
<td>$S_1, S$</td>
</tr>
<tr>
<td>2.923</td>
<td>2.84</td>
<td>2.924</td>
<td>2.921</td>
<td>$S_2, S$</td>
</tr>
<tr>
<td>2.921</td>
<td>2.923</td>
<td>2.84</td>
<td>2.924</td>
<td>$S_3, S$</td>
</tr>
<tr>
<td>2.924</td>
<td>2.921</td>
<td>2.923</td>
<td>2.84</td>
<td>$S_4, S$</td>
</tr>
</tbody>
</table>

The average current values of $B_i$ when sub-circuits $S_i$ and $S$ were working are shown in Figure 17a. When voltage $V_4$ was lower than the other cell voltages, all single-cell voltages before and after the work of the balancing sub-circuit are shown in Figure 17b.
Figure 17. (a) Power battery pack discharging current and all single-cell currents; (b) All single-cell voltages before and after the work of the balancing sub-circuits.

Figure 17a shows that $I_{eq1} = 294$ mA, $I_{eq2} = 297$ mA, $I_{eq3} = 294$ mA, and $I_{eq4} = 301$ mA when the power battery pack was discharging at a current of 500 mA. The equalization current $I_{eq}$ of the balancing sub-circuit reached up to 0.1 C, showing that equalization circuit could reduce or even eliminate the discharge current of the cell with lower voltage. Figure 17b shows that, after the work of the equalization circuit, all single-cell voltages converged. In the suspended state after discharging, the initial voltages of the four cells were as shown in Table 4.

Table 4. Initial voltages of all cells in the suspended state after discharging.

<table>
<thead>
<tr>
<th>$V_1$</th>
<th>$V_2$</th>
<th>$V_3$</th>
<th>$V_4$</th>
<th>Working Switch</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.823</td>
<td>2.886</td>
<td>2.885</td>
<td>2.884</td>
<td>$S_1, S$</td>
</tr>
<tr>
<td>2.884</td>
<td>2.823</td>
<td>2.886</td>
<td>2.885</td>
<td>$S_2, S$</td>
</tr>
<tr>
<td>2.885</td>
<td>2.884</td>
<td>2.823</td>
<td>2.886</td>
<td>$S_3, S$</td>
</tr>
<tr>
<td>2.886</td>
<td>2.885</td>
<td>2.884</td>
<td>2.823</td>
<td>$S_4, S$</td>
</tr>
</tbody>
</table>
The average current values of \( B_i \) when balancing sub-circuits \( S_i \) and \( S \) were working are shown in Figure 18a. When the voltage \( V_3 \) was lower than the other cell voltages, all single-cell voltages before and after the work of the balancing sub-circuits are shown in Figure 18b.

Figure 18. (a) Average current values of \( B_i \) during operation of sub-circuits \( S_i \) and \( S \); (b) All single-cell voltages before and after the work of the balancing sub-circuits

Figure 18a shows that \( I_{eq1} = 295 \) mA, \( I_{eq2} = 298 \) mA, \( I_{eq3} = 300 \) mA, and \( I_{eq4} = 299 \) mA in the suspended state after discharging. The equalization current \( I_{eqi} \) of the balancing sub-circuit reached up to 0.1 C, showing that equalization circuit could transfer energy from higher-energy cells to lower-energy cells. Figure 18b shows that, after the work of the equalization circuit, all single-cell voltages converged.

6. Conclusions

Given the effects of variations in the lifecycle durations of series battery packs and the present state of equalization circuits, this paper proposes a novel voltage equalization circuit based on the buck-boost circuit. To verify the effectiveness of the proposed equalization circuit, a simulation model and experimental test platform were built. The simulation and experimental results show that the proposed equalization circuit can reduce the charging current of the higher-voltage cell during charging and
decrease the discharging current of the lower-voltage cell during discharging. The circuit can discharge the higher-voltage cell in the suspended state after charging and charge the lower-voltage cell in the suspended state after discharging. This equalization circuit is characterized by high speed and large equalization currents. Future research will focus on using the single-cell state of charge as an index of inconsistency to achieve higher precision of the equalization circuit.

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Author Contributions

This research article has five authors. The circuit structure was designed by Xiangwei Guo and Longyun Kang. Xiangwei Guo and Zhizhen Huang conceived the research methods and control strategies. Xiangwei Guo, Yuan Yao and Huizhou Yang designed and performed the experiments. Longyun Kang contributed the experimental environment. Xiangwei Guo wrote the paper.

Conflicts of Interest

The authors declare no conflict of interest.

References


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