Research on Balanced Management Topology of Series Battery Pack

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Abstract. With the rapid development of renewable energy, energy storage battery technology has made great progress, and it has also caused the rapid development of electric vehicles. There is an inevitable difference between a large number of battery cells in the energy storage battery pack of electric vehicles. This difference will increase with time, and ultimately affect the safe operation of electric vehicles. Aiming at the problem of voltage imbalance in series battery packs, an improved balanced topology based on energy storage inductors is proposed. The basic working principle of the active balanced topology is analyzed, and the charging and discharging process of the balanced topology is theoretically derived. Finally, the simulation model of the balanced control during the charging and discharging process of the battery pack is built using MATLAB/Simulink. The simulation results show that the battery pack has a good balance effect during charging and discharging, which can provide an effective solution to the balance problem of series battery packs.

1. Introduction

Environment and energy are two important problems for sustainable development in the world. Under the theme of global energy conservation and emission reduction, energy storage batteries are widely used in power systems and new energy electric vehicles. In recent years, China has been committed to the development of the battery energy storage industry, and the support and investment of the government and enterprises for the energy storage industry is also growing [1]. To meet the requirements of voltage, power, and so on, a series connection mode of multiple battery units is generally adopted. After the battery cells are grouped, the external and internal factors lead to the inconsistency of the characteristics of the single battery in the battery pack, which will cause the inconsistency in the whole charging and discharging process of the battery pack, which has a very adverse impact on the life, capacity and safe operation of the battery pack [2-4]. Without the use of a battery equalization module, the voltage, capacity, energy conversion efficiency and charge-discharge efficiency of each cell will decrease with time. If no measures are taken, the battery will be over-charged, over-discharged, and "reverse polarity" phenomenon, which will cause the battery to overheat and cause the battery to burn and explode. Therefore, battery balanced management is very necessary for prolonging battery life and is an essential part of the battery management system (BMS).

Battery equalization circuit topology can be divided into passive equalization and active equalization. The passive equalization circuit uses the energy consumption resistor in parallel in the single battery to
discharge and consume the high-voltage battery cell, to realize the balance of the voltage of each cell in the battery pack [5,6]. Due to its simple circuit, low cost, and simple control logic, the passive equalization circuit is widely used in engineering applications. However, its disadvantages are also very obvious, such as energy consumption and heat dissipation in the process of battery equalization. The active equalization circuit uses inductors, capacitors, and DC-DC converters to transfer the energy from the single battery with high voltage in the battery pack to the single battery with low voltage by using energy storage elements such as inductors and capacitors or realize the energy transfer between battery groups and between battery cells through DC-DC converter [7]. At present, active equalization is an important research direction of equilibrium management. It has the advantages of diversified topology structure, high equilibrium efficiency, large power level, and flexible equilibrium optimization control through the software algorithm, which has great market potential and market application demand.

As one of the first countries to study the battery management system, the United States developed the Smart Guard battery management system earlier for commercial use [8]. German Menzer Electronics Co., Ltd and Werner Retzlaff Co., Ltd. jointly developed the Badicoach battery management system [9], which can realize the management of different types of battery packs. As early as the end of the 20th century, Japan's Aikawa industry began to study electric vehicles. Nowadays, the BMS technology in Japan has developed very maturely. Among them, the battery management system of the hybrid vehicle Prius developed by Toyota is the most typical [10]. Under the promotion of the 863 programs, China's battery management system has also made great breakthroughs [5,7]. In reference [11], an active equalization topology is proposed, which does not need to be equipped with energy storage components, and the energy is directly transferred between the single battery connected by the switch, thus greatly simplifying the equilibrium topology, improving the equalization efficiency and reducing the equalization time. However, the flexibility of the topology is poor and it can not be a modular design. The active equalization topology based on photovoltaic switch is proposed in reference [12]. The control unit generates PWM wave through the voltage, current, and temperature parameters of the battery pack, and realizes the equalization of the battery pack by controlling PWM. The scheme can manage many parameters of the battery pack, but the control logic is complex and difficult to be popularized. In reference [13], an active equalization topology based on inductor is proposed. By controlling the on-off of power electronic switch, the direction and size of equalization current transfer can be controlled, and the inductor is used to store energy, to realize energy transfer between single battery with different state of charge. In this topology, the number of control switches is too large and the switching loss is large. The buck-boost equalizer proposed in reference [14] uses a simple isolated DC-DC converter, and the equalization effect of the equalizer is positive, but its circuit structure is more traditional, the design is more complex, and its scalability is poor. The LLC resonant converter is used to transfer the charge from the highest voltage battery to the lowest battery, which improves the equalization speed and efficiency[15].

In 2020, there have been several vehicle fire disasters during charging and driving. The dynamic balance problem in the process of battery charging and discharging has become the primary problem to be solved. Considering the advantages and disadvantages of different equalization schemes, and to meet the requirements of fast equalization speed and good equalization effect, a voltage equalization topology based on inductor is proposed in this paper. The basic working principle of the topology and the theoretical analysis of the charging and discharging process are analyzed, and the simulation model is built. The simulation results prove that the topology proposed in this paper has a better balance effect in the charging and discharging processes of the battery pack.

2. Analyze the equalization topology

2.1. Structure of the active balancing circuit
The active equalization circuit based on inductor proposed in this paper is shown in figure 1. The equalization circuit is composed of a single battery, control switches, a diode, and an inductor. The two ends of each cell are connected with the inductor through control switches to form a charging and
discharging circuit. The energy storage inductor stores energy in the charging circuit, releases energy in the discharge circuit, and realizes the energy transfer between cells with different voltages through a charging and discharging cycle. A diode is connected in series on each equalization branch with power electronic fast switch to avoid reverse current and short circuit of energy. The control switches can be MOSFET, IGBT, thyristor, and other power electronic switches. The number of control switches is related to the balanced cell. If \( n \) cells need to be balanced, \( 2(n + 1) \) control switches are required. For the equalization circuit, when the voltage difference \( \Delta V = V_{\text{max}} - V_{\text{min}} > 10\text{mV} \), the equalization circuit starts to run, otherwise stops running, where \( V_{\text{max}} \) is the highest voltage value of a single battery in the battery pack, and \( V_{\text{min}} \) is the lowest voltage value of a single battery in the battery pack.

![Figure 1. Active balancing circuit based on the inductor.](image)

**2.2. Principle of operation of the active balancing topology**

It is assumed that the voltage of single battery B1 is the highest and that of B4 is the lowest in the same battery pack, and the voltage difference between them is greater than the threshold value \( \Delta V = 10\text{mV} \). The working principle of the equalization circuit is illustrated by the charging process of single battery B1 to B4. The equalization circuit is shown in figure 2.

Single battery B1 charges the inductor L: close MOSFET M1, at this time, the current starts from the positive pole of the single battery B1, passes through diode D1 and MOSFET M1, reaches inductor L, passes through diode D9, and the current returns to the negative pole of single battery B1 to form an inductive charging circuit. In the discharge link of inductor L to the single battery B3, the MOSFET M1 is turned off, and the MOSFET M5 is closed. The inductor L enters the discharge state, and the discharge current direction is the same as the charging current. Starting from the negative pole of the inductor, the current enters the positive pole of the single battery B4 through the field diode D11 and then flows out from the negative pole. Through the diode d5 and the MOSFET M5, the current returns to the positive pole of the inductor, forming an inductive discharge circuit to charge the single battery B4. In this way, the charging link of the single battery B1 to the inductor L and the discharging link of the inductor L to the single battery B3 is repeated until the battery cells reach equilibrium.

The equalization process can be divided into equalization between adjacent single battery and equalization between non-adjacent single battery. The equalization circuit is a conventional buck-boost circuit, which can realize the charging or discharging process of the specified battery cell. The following specifically analyzes the equalization process between adjacent single battery, that is, battery B1 charges B2, and the equalization process between non-adjacent battery cells, that is, B1 charges B4.
2.2.1. Equalization of non-adjacent batteries.

The equalization process of the non-adjacent battery is shown in the figure 3, and it is shown as the discharge process from B1 to B4. The equalization circuit is similar to that of a buck-boost DC-DC converter. The driving signal and inductor current waveform during the equalization process are shown in figure 4.

It can be seen from figure 3 that when M5 is normally closed, the circuit is a conventional voltage rise and drop circuit, which can realize the charging or discharging process of B1 to B4.

1. Inductor charging link \([t_0 \rightarrow t_1]\): When the MOSFET M1 is closed at the same time, the inductor current increases with a constant slope.

\[
i_L(t) = \frac{v_{BI}}{L} t
\]

\[
i_{peak} = \frac{v_{BI}}{L} DT_2
\]

Inductor charging link \([t_0 \rightarrow t_1]\) The energy transferred from battery B1 to inductor L is

\[
E_{B1,\text{discharge}} = \frac{1}{2} i_{peak} \times DT_3 = \frac{1}{2} \frac{v_{BI}}{L} (DT_2)^2
\]

2. Inductor discharge link \([t_1 \rightarrow t_2]\): When MOSFET M1 is turned off and MOSFET M5 is closed, the inductor current decreases with a constant slope.

\[
i_L(t) = \frac{v_{BI}}{L} DT_3 - \frac{v_{BS}}{L} t
\]

Inductive discharge link \([t_1 \rightarrow t_2]\) The energy transferred from the inductor to battery B4 is

\[
E_{B4,\text{charge}} = \frac{1}{2} \frac{v_{BI}}{L} (DT_3)^2
\]
2.2.2. Equalization of adjacent cells.

The equalization process of adjacent batteries is shown in figure 5, which shows the charging process from B1 to B2. It can be seen from figure 5 that when MOSFET M3 and MOSFET M7 are normally closed, the circuit is a conventional voltage rising circuit, which can realize the charging or discharging process of B1 to B2. The driving signal and inductor current waveforms in the equalization process are shown in figure 6. The theoretical analysis process is similar to that of the equalization of non-adjacent batteries, we won’t discuss it in this part.

![Figure 4. Gate signal and inductor current.](image)

![Figure 5. Balanced circuit diagram of adjacent cells.](image)
Figure 6. Adjacent battery balancing circuit drive signal and inductor current.

3. Theoretical analysis

3.1. Theoretical analysis of charge and discharge of energy storage inductor

When battery B1 charges the inductor, the voltage of inductor L can be expressed as:

\[ V_L = L \frac{di_L}{dt} = V_B1 \] (6)

Equations (6) can be rewritten as follows:

\[ \frac{V_B1}{L} = \frac{di_L}{dt} = \frac{di_L}{D \cdot T} \] (7)

Where \( D \) is the duty cycle.

The current of inductor L can be written as:

\[ \Delta i_{\text{om}}(t) = \frac{V_{B1}}{L} \cdot D \cdot T \] (8)

Inductor L to B3 in the charging process:

\[ V_L = L \frac{di_L}{dt} = -V_{B3} \] (9)

The discharge current of inductor L can be expressed as:

\[ \Delta i_{\text{off}}(t) = -\frac{V_{B3}}{L} \cdot (1 - D) \cdot T \] (10)

As it is known, in steady-state the inductor current change in a period is zero.

\[ \frac{i_{\text{on}}}{L} + \frac{i_{\text{off}}}{L} = 0 \] (11)

\[ \frac{V_{B1}}{L} \cdot D \cdot T - \frac{V_{B3}}{L} \cdot (1 - D) = 0 \] (12)

If the ratio of cell B1 to cell B2 is \( \partial \), then

\[ \partial = \frac{V_{B3}}{V_{B1}} = \frac{D_1}{1 - D_1} \] (13)

Among them, the cell ratio parameter \( \partial \) can be used to control the duty cycle, improve the equalization speed, and reduce the equalization current.

3.2. Calculation of maximum current

When the battery B1 charges the inductor L, the MOSFET M1 and M9 are on, and the current \( i_L \) gradually increase. The battery B1 charges to the inductor L. The MOSFET conduction time \( t_{on} \) determines the maximum value of inductor current \( i_{L_{max}} \), and equation (14) is obtained.

\[ V_{B1} = R_{on}i_c + L \frac{di_L}{dt} (0 < t < t_{on}) \] (14)
Where $R_{on}$ is the total resistance when M1 is on, $t_{on}$ is the on-time of the MOSFET. By solving the equation (14), the general solution equation (15) of the equation can be obtained.

$$i_L = \frac{V_{B1}}{R_{on}} (1 - e^{-\frac{R_{on}}{L}t})(0 < t < t_{on})$$  \hfill (15)

When $t = t_{on}$, the inductor current reaches the maximum value, as shown in equation (16).

$$i_L = \frac{V_{B1}}{R_{on}} (1 - e^{-\frac{R_{on}}{L}t})(t = t_{on})$$  \hfill (16)

The process of charging battery B2 with inductor L is a first-order full response circuit. Therefore, the first-order full response equation can be obtained as shown in equation (17).

$$i_L = I_{max}e^{-\frac{R_{off}}{L}(t-t_{on})} - \frac{V_{B2}}{R_{off}}(1 - e^{-\frac{R_{off}}{L}(t-t_{on})})(t_{on} < t < t_d)$$  \hfill (17)

4. Simulation results

To verify the feasibility and effectiveness of the equilibrium topology, an equilibrium simulation model is built in the MATLAB / Simulink simulation platform. The battery model of the simulation platform is selected for the single battery, which can set the parameters of the battery such as nominal voltage, rated capacity, internal resistance, cut-off voltage, fully charged voltage, to verify the accuracy of the cell model. The parameters of the battery model are set according to the parameters of the supfire18650 lithium battery produced by a factory. The parameters of the battery model are shown in table 1 below, which can better describe the charging and discharging characteristics of the battery. The value of the energy storage inductor is 60 $\mu$H and the switching frequency is 1kHz. The initial SOC of single battery B1 and battery B4 is set at 98% and 10%. The simulation step is fixed step and the solver is set as the discrete mode. The simulation model built in Simulink is composed of an equalization circuit, control module, and scope. The control module is used to control the on-off of the switch and judge the equilibrium condition, and the scope is used to observe the waveform.

| Parameters                  | Unit | Value |
|-----------------------------|------|-------|
| Rated capacity              | Ah   | 1.8   |
| Nominal voltage             | V    | 3.7   |
| Internal resistance         | $m\Omega$ | $\leq 4$ |
| Cut-off voltage             | V    | 2.7   |
| Fully charged voltage       | V    | 4.5   |

4.1. Result of static process equilibrium

Figure 7 shows the voltage variation curve of a single battery obtained by simulation under the working condition of the equalization topology. The initial voltage of two single batteries B1 and B2 are 3.84v and 3.23v respectively, and the pressure difference between them is 610mv, which is greater than the threshold value of 10mV. When the equalization circuit is turned on, the energy of battery cell B1 is transferred to cell B2 through the equalization circuit, and the voltage of single battery B1 drops and the voltage of single battery B1 increases As shown in the figure. 8, the voltage difference decreases with a fixed slope, and finally, the voltage tends to 3.32v, and the voltage inconsistency is improved. The inductor voltage waveform is shown in figure 9.
4.2. Result of discharge process equalization

When the battery pack is discharging, the initial voltage of the battery is set to be 3.84 V and 3.23 V respectively. When the discharge load is 40 Ω resistance, the balance strategy is: voltage difference $\Delta V$ is greater than the threshold value, the equalization circuit starts to work until the voltage difference between the two batteries is within 10 mV. The simulation results are shown in the figure 10 and figure 11. It can be seen that the voltage of battery B1 and battery B2 begins to drop, and the voltage tends to
be consistent after about 6.4 s. the equalization module stops working and the equalization is completed. The voltage of the battery cell begins to decrease gradually during the discharge process.

![Figure 10. The cells voltage during the discharging process.](image)

![Figure 11. Voltage difference during discharge process.](image)

4.3. Result of charging process equalization

When the battery pack is discharging, the initial voltage of the battery is 3.84v and 3.23v, the charging voltage is 7V, the charging current is 0.2A, and the equalization strategy is: voltage difference $\Delta V$ is greater than the threshold value, the equalization circuit starts to work until the voltage difference between the two batteries is within 10mV. After the simulation, the simulation results as shown in figure.12 and figure.13 are obtained. It can be seen from the Figure that the battery B1 decreases and B2 voltage rise, realizing the energy transfer. After about 6.2s, the battery cell voltage tends to be the same, the equalization module stops working, and the equalization is completed. The voltage of battery cell B1 and B2 begins to rise gradually during the charging process.
5. Conclusions
In this paper, aiming at the balance problem of the battery management system, a simple and practical, high reliability and versatility of the equalization topology is proposed. Moreover, the battery pack topology can effectively reduce the number of battery packs, effectively reduce the number of battery packs, and effectively ensure the safe operation of the battery pack. The simulation results show that the topology can achieve a good equalization effect in the process of system charging and discharging. The topology structure is simple and can realize modularization. It provides an effective solution for the equalization problem of series batteries.

In this stage, we only study the feasibility, practicability, and equalization effect of the topology. In the future, we plan to carry out further research in the following directions: increasing the number of batteries in series, designing a battery equalization algorithm, optimizing the control of equilibrium topology; active equalization control strategy of the battery module.

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