Design of active equalizer for lithium-ion battery pack based on double-tiered modular resonance

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ABSTRACT
The energy balance between individual lithium-ion batteries in electric vehicles is an important factor that affects the efficiency and long-time operation of the entire system. In the conventional modular switched capacitor method, small pressure difference between the batteries at the end of the equalization and the need for multi-stage transmission may cause the low efficiency of the equalization, slow speed and so on. To solve the issues, the control method of three-resonant-state LC converters is adopted in this paper. The resonance process not only improves the transferable energy of the capacitor, but also realizes the zero-current switching of the circuit, reducing the circuit switching loss and electromagnetic interference. A double-tiered modular resonance equalization structure is also proposed to provide more energy transfer paths and larger equilibrium current. By means of this, the inconsistency between the cells can be eliminated more quickly and efficiently when energy needs to be transferred in multiple stages. Comparative experiment is conducted by constructing a simulation platform and an experimental platform to demonstrate the superiority of the double-tiered resonance equalization.

1. Introduction

Forced by the pressure of environmental pollution and the depletion of non-renewable resources, many countries in the world have set a timetable for the ban on the sale of fuel vehicles. China has also put it on the agenda recently. The trend of the development of new energy vehicles is irresistible, especially the lithium-ion-batteries-powered electric vehicles (Zheng, Chen, & Ouyang, 2018). However, the voltage of a single-cell lithium battery is too small to provide a higher supply voltage, so a multi-cell battery is usually used in series (Wang, Polis, Yin, Chen, & Fu, 2012; Hsieh, Wu, & Chen, 2012). Due to manufacturing process problems or external temperature, humidity and other factors, there will be some differences between the batteries. And this difference will be increased in the repeated use of the charge and discharge process, which will seriously affect the service life of the battery and could increase the risk of explosion (Javier, Enrique, & Isabel, 2015). Therefore, in order to eliminate or reduce this inconsistency, it is very important to effectively equalize each battery.

At present, the common lithium-ion battery equalization methods can be divided into two categories: passive equalization and active equalization. Passive equalization is the earliest and most widely used method. The basic principle of this method is to equalize the battery cell by using a parallel resistance at both ends of the battery to consume the energy in the battery which has more energy. Instead, active equalization equalizes energy transfer through energy storage elements. This method mainly includes the inductance energy storage equalization and the capacitor energy equalization. The equalization speed of the equalizer with inductive energy storage is high and the current of the equalization current can be controlled (Zheng, Liu, He, & Zeng, 2017; Ma, Duan, Sun, & Chen, 2018; Lu, Liu, Yin, & Lin, 2016). This method utilizes the principle that the current passing through the inductor cannot be mutated which leads to the difficulty in controlling the process of releasing energy after the energy storage of the inductor, so it limits the circuit structure of the method. On the contrary, the structure of an equalizer with capacitor energy storage is very variable (Kim, Kim, Kim, & Moon, 2014; Yuan & Wai, 2016), with simple control and high efficiency of equalization (Zhang, Sun, Liang, & Zhao, 2016). However, the equilibration speed is greatly affected by the voltage difference between the batteries. When the pressure difference between the batteries is small, the equilibration speed is extremely slow or cannot be performed (Javier, Enrique, Maria, & Miguel, 2014). The works...
by Shang, Zhang, Cui, and Guerrero (2015), Liu and Xia (2013), Ye, Cheng, and Yeung (2012) and Li, Zhou, Wang, and Fu (2017) proposed the method of the LC series resonant and the double-tiered quasi-resonant equalization respectively, which has improved the energy transfer ability to some extent. But when the pressure difference between the batteries is small, the equalization speed is also very slow. Literature Lee, Chung, Sung, and Kang (2015) introduces the structure of the H-bridge into the equalizer circuit while using LC resonance, by controlling the conduction of the bridge arm to change the polarity of the capacitor. This circuit has a higher equalization speed even when the battery is at zero differential voltage. However, the control is slightly complicated. The literature Shang, Cui, Zhang, and Zhang (2017) proposes a three-resonant-state LC equalization method. The control of a single circuit module is relatively simple and the equalization speed is high. However, the circuit design is a single-tiered structure, which will significantly reduce the equalization speed and efficiency when energy needs to be transferred in multiple stages.

Based on a three-resonant-state LC method, this paper proposes a double-tiered modular resonant equalization structure and optimizes the design of the single-tiered equalization circuit. The paper first introduces the double-tiered modular equalization structure and working principle. Secondly, the working process and equalization efficiency of three-resonant-state LC are analysed and calculated. Then the circuit is verified through simulation. Finally, a high-precision voltage acquisition circuit and an equalization circuit are designed to verify the experiment. The simulation and experimental results show that the double-tiered modular equalization structure can effectively improve the equalization speed and efficiency of the battery.

2. Double-tiered modular resonant equalized topology

Figure 1 shows the single resonant equalization module proposed in this paper. Each equalization module can realize energy transfer between two adjacent cells, which includes a storage inductance, a storage capacitor and five MOSFET switches. Here, the inductor and the capacitor are connected in series to form a resonator, which increases the capacitor voltage by resonance, so that more energy can be stored and released. The basic principle of this circuit works as follows: by controlling the corresponding switch, the energy in high-energy battery is stored in the capacitor first, then the energy in the capacitor is transferred to low-energy battery. However, due to the existence of the line resistance, the capacitor cannot completely release the energy, and the resonant current and the capacitor voltage will decrease in the next resonant cycle. Therefore, it is necessary to change the polarity of the capacitor voltage again through one more resonance. So the cycle will continue until the two battery energy is equalized.

Since each equalization module contains two cells upper and below, there are two modes of equalization pattern. The following description with reference to Figure 1.

**Working mode I**: When the energy of the top battery $B_1$ is greater than the energy of the bottom battery $B_2$. First, turn on the switch $Q_1$ and switch $Q_3$ for about $\Delta t$ seconds, the high-energy battery $B_1$ is connected in series with switch $Q_1$ inductance $L_1$ capacitance $C_1$ and switch $Q_3$ to form a loop. The energy is stored in the capacitor $C_1$. Second, turn on the switch $Q_2$ and switch $Q_4$ for about $\Delta t$ seconds, the low-energy battery $B_2$ is connected in series with switch $Q_2$ inductance $L_1$ capacitance $C_1$ and switch $Q_4$ to form a loop. The energy in the capacitor is released to the battery $B_2$. Finally, turn on the switch $Q_5$ for $\Delta t$ seconds. The inductance $L_1$ is connected in series with capacitor $C_1$ and switch $Q_5$ to form a loop. The circuit oscillates to change the polarity of the capacitor.

**Working mode II**: When the energy of the bottom battery $B_2$ is greater than the energy of the top battery $B_1$. First, turn on the switch $Q_2$ and switch $Q_4$ for about $\Delta t$ seconds, the battery $B_2$ releases energy into the capacitor $C_1$. Second, turn on the switch $Q_1$ and switch $Q_3$ for about $\Delta t$ seconds. The energy in the capacitor $C_1$ is released to the low energy battery $B_1$. Finally, turn on the switch $Q_5$ for $\Delta t$ seconds. It also makes the circuit oscillate and change the polarity of capacitance.

In the same way, for other equalization modules, it is necessary to map the switch tube to the same position for control.

Figure 2 is a double-tiered modular resonant equalization structure consisting of four batteries. The internal tier comprises equalization module 1, equalization module 2 and equalization module 3, which are an equalization module between two adjacent single cell batteries. The
equalization module 4 is an outer tier, which consists of two adjacent batteries and an integrated module. Similarly, if \( N (N \geq 4) \) is connected in series, the number of inner tier equalization modules is \( N-1 \), and the number of external equalization modules is \( N/2-1 \). If \( N \) is an odd number, the terminal or initial battery does not participate in forming the external equalization module. The circuit structure and working principle of the external equalization module is the same as that of the internal equalization module. Under certain conditions, the external and internal equalization modules working at the same time can significantly improve the equalization speed and efficiency.

### 3. Resonance equalization process analysis and efficiency analysis

#### 3.1. Balanced process

In the process of equalization, both the internal equalization module and the external equalization module basically work in the same way. The difference is that the double-tiered battery cell is made of two series, so the voltage is higher. It is assumed here that the energy of battery \( B_1 \) is larger than \( B_2 \). Figure 3 shows some pivotal waveforms when the module circuit is equalized. In the figure, from top to bottom, there are the driving signal \( V_{GS1} \) of switch \( Q_1 \) and \( Q_3 \), the driving signal \( V_{GS2} \) of switch \( Q_2 \) and \( Q_4 \), the driving signal \( V_{GS3} \) of switch \( Q_5 \), the voltage \( V_{C1} \) on both ends of the storage capacitance \( C_1 \), the resonant current \( i_L \) through inductance \( L_1 \), the discharged current \( i_{B1} \) of battery \( B_1 \) at equilibrium, the charged current \( i_{B2} \) of battery \( B_2 \) at equilibrium. Equalization can be divided into three processes which are analysed with reference to Figures 1 and 3.

(1) **Capacitor charging process:**

Turn on switches \( Q_1 \) and \( Q_3 \). Battery \( B_1 \) connect with all parasitic resistances in the current path \( R_s \), inductance \( L_1 \), capacitor \( C_1 \) in series. Since capacitor is used as an energy storage component, a non-polarity capacitor with low self-discharge should be selected. Generally, ceramic capacitors or polypropylene film capacitors are optional. The capacity of these capacitors is generally far less than the capacity of the battery. Therefore, in this process, battery \( B_1 \) can be approximately seen as a voltage source. The equivalent circuit model of this process is shown in Figure 4.

If the capacitor voltage is at the initial moment is \( V_{t0} \), then at \( t_0 - t_1 \), the resonant current and the capacitor...
Capacitor discharges the battery where voltage are:

\[ i_{L_1}(t) = \frac{V_{B_1} - V_t}{\omega_L L_1} e^{-\delta(t-t_0)} \sin \omega_r(t-t_0), \quad (1) \]
\[ V_{C_1}(t) = (V_{B_1} - V_t) \left\{ 1 - \frac{e^{-\delta(t-t_0)}}{\sqrt{1 - \rho^2}} \cos(\omega_r(t-t_0)) \right\} + V_t, \quad (2) \]

where
\[ \omega_r = \sqrt{\frac{1}{L_1 C_1} - \left( \frac{R_s}{2L_1} \right)^2} = \frac{1}{\sqrt{L_1 C_1}} \sqrt{1 - \left( \frac{R_s}{2\sqrt{L_1 C_1}} \right)^2} = \omega_n \sqrt{1 - \rho^2} \quad (3) \]

and \( \delta = \frac{R_s}{2L_1}, \) \( \omega_n = 1/\sqrt{L_1 C_1}, \) \( \rho = \frac{R_s}{2\sqrt{L_1 C_1}}. \)

The duration \( \Delta t \) of the capacitor charging process is half of the resonant period. So:
\[ \Delta t = t_1 - t_0 = \frac{\pi}{\omega_r}, \quad (4) \]

After \( \Delta t, \) the resonant current becomes zero and the capacitor voltage reaches the maximum value \( V_{t_1}. \) At this time:
\[ V_{t_1} = (V_{B_1} - V_t) \left\{ 1 + \frac{e^{-\delta(\Delta t)}}{\sqrt{1 - \rho^2}} \right\} + V_t, \quad (5) \]

In this process, the higher the voltage \( V_1 \) of the high-energy battery is, the larger the discharge current is and the higher the equalization speed is.

(2) Capacitance discharge process:

Turn on switches \( Q_2 \) and \( Q_4. \) If the line circuit is \( R_s, \) the capacitor discharges the battery \( B_2 \) since the capacitor voltage \( V_{t_1} \) is larger than the battery \( B_2 \) voltage \( V_{B_2} \) at this time. This process is similar to the charging process. The equivalent circuit model is shown in Figure 5.

Then in the capacitor discharge process \( t_1 - t_2, \) the equation of the circuit resonant current and capacitor voltage is:
\[ i_{L_1}(t) = \frac{V_{B_2} - V_t}{\omega_L L_1} e^{-\delta(t-t_1)} \sin \omega_r(t-t_1), \quad (6) \]
\[ V_{C_1}(t) = (V_{B_2} - V_t) \left\{ 1 - \frac{e^{-\delta(t-t_1)}}{\sqrt{1 - \rho^2}} \cos(\omega_r(t-t_1)) \right\} + V_t. \quad (7) \]

This process will also last for half a resonant period. After a half resonance period \( \Delta t, \) that is, at time \( t_2, \) the resonant current in the circuit becomes zero, and the capacitor voltage reaches the minimum value \( V_{t_2}, \) and its value is:
\[ V_{t_2} = (V_{B_2} - V_t) \left\{ 1 + \frac{e^{-\delta(\Delta t)}}{\sqrt{1 - \rho^2}} \right\} + V_t, \quad (8) \]

In this process, the larger the voltage of the low-energy battery \( B_2 \) is, the smaller the charging current to it is, and the lower the equalization speed is.

(3) Capacitor polarity reversal process:

Turn on switch \( Q_3, \) assuming that the total impedance of the line is still \( R_s. \) Different from the above two processes, this process becomes a RLC series resonance without voltage source, and it depends on the residual energy on the capacitor to oscillate. The equivalent circuit model is shown in Figure 6.

The circuit resonant current and capacitor voltage at \( t_2 - t_3 \) are:
\[ i_{L_1}(t) = \frac{V_{B_2} - V_t}{\omega_L L_1} e^{-\delta(t-t_2)} \sin \omega_r(t-t_2), \quad (9) \]
\[ V_{C_1}(t) = -V_2 \left\{ 1 - \frac{e^{-\delta(t-t_2)}}{\sqrt{1 - \rho^2}} \cos(\omega_r(t - t_2)) \right\} + V_2. \]  

(10)

Similarly, the minimum value of the capacitor voltage is \( V_{t_3} \) after \( \Delta t \), and the polarity of the capacitor is opposite to the polarity at time \( t_2 \).

\[ V_{t_3} = -V_2 \left\{ 1 + \frac{e^{-\delta(\Delta t)}}{\sqrt{1 - \rho^2}} \right\} + V_2. \]  

(11)

When \( R_s = 0 \), that is, when the line is lossless \( V_{t_3} = -V_2 \). Equations (5), (8), and (11) yield

\[ V_{t_1} = \frac{V_{B_1} + k^2V_{B_2}}{k^2 - k + 1}, \]  

(12)

\[ V_{t_2} = \frac{V_{B_2} - kV_{B_1}}{k^2 - k + 1}, \]  

(13)

\[ V_{t_3} = \frac{k(kV_{B_1} - V_{B_2})}{k^2 - k + 1}, \]  

(14)

Figure 7. Simulation results. (a) Single-tiered resonance equalization simulation and (b) double-tiered resonance equalization simulation.
where

\[ k = \frac{e^{-\delta(\Delta t)}}{\sqrt{1 - \rho^2}}. \]  

(15)

### 3.2. Analysis of equalized energy efficiency

Since one equalization period contains three processes of the same resonant frequency, one equalization period can be expressed as:

\[ T_s = 3\Delta t. \]  

(16)

The average discharge current in battery \( B_1 \) during one cycle is:

\[
\begin{align*}
\bar{i}_a &= \frac{1}{T_s} \frac{V_{B_1} - V_{t_3}}{\omega r L_1} \frac{\delta}{\delta^2 + \omega^2} e^{-\delta(\Delta t)} \times \left\{ \sin \omega r(\Delta t) + \frac{\omega r}{\delta} \cos \omega r(\Delta t) \right\}. 
\end{align*}
\]

(17)

Then, the average power \( P_a \) delivered by the battery \( B_1 \) is:

\[
\begin{align*}
P_a &= V_{B_1} \bar{i}_a = \frac{1}{T_s} \frac{V_{B_1} - V_{t_3}}{\omega r L_1} \frac{\delta}{\delta^2 + \omega^2} e^{-\delta(\Delta t)} \times \left\{ \sin \omega r(\Delta t) + \frac{\omega r}{\delta} \cos \omega r(\Delta t) \right\}.
\end{align*}
\]

(18)

Similarly, the average charge current \( \bar{i}_b \) of the battery \( B_2 \) in one cycle and the absorbed balance power \( P_b \) are:

\[
\begin{align*}
\bar{i}_b &= \frac{1}{T_s} \frac{V_{B_2} - V_{t_1}}{\omega r L_1} \frac{\delta}{\delta^2 + \omega^2} e^{-\delta(\Delta t)} \times \left\{ \sin \omega r(\Delta t) + \frac{\omega r}{\delta} \cos \omega r(\Delta t) \right\},
\end{align*}
\]

(19)

\[
\begin{align*}
P_b &= -V_{B_2} \bar{i}_b = -V_{B_2} \frac{1}{T_s} \frac{V_{B_2} - V_{t_1}}{\omega r L_1} \frac{\delta}{\delta^2 + \omega^2} e^{-\delta(\Delta t)}
\end{align*}
\]

\[
\times \left\{ \sin \omega r(\Delta t) + \frac{\omega r}{\delta} \cos \omega r(\Delta t) \right\}. 
\]

(20)

The equilibrium efficiency \( \eta \) of the balanced system is:

\[
\eta = \frac{P_b}{P_a} = \frac{V_{B_2} (1 - k) V_{B_2} - V_{B_1}}{V_{B_1} V_{B_2} - V_{t_3}} - \frac{V_{B_2} (1 - k) V_{B_2} - V_{B_1}}{V_{B_1} V_{B_2} - V_{t_3}}.
\]

(21)

Under the same circuit parameters, if the energy is transferred through \( n \) equalization modules, the efficiency of this part of the energy is:

\[
\eta' = (\eta)^n.
\]

(22)

This shows that the more times the energy passes, the lower the efficiency will become. Therefore, efficiency can be improved by increasing the efficiency of a single module or reducing the number of energy transfer.

### Table 1. Voltage detection results.

| Battery number | Actual value/(V) | 1st Test value/(V) | 2nd Test value/(V) | 3rd Test value/(V) | 4th Test value/(V) | 5th Test value/(V) | 6th Test value/(V) | 7th Test value/(V) | Max error/(mV) |
|----------------|------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|----------------|
| B1             | 2.859            | 2.858              | 2.859              | 2.859              | 2.858              | 2.858              | 2.858              | 2.858              | 1               |
| B2             | 3.100            | 3.101              | 3.102              | 3.100              | 3.102              | 3.100              | 3.100              | 3.100              | 2               |
| B3             | 3.247            | 3.246              | 3.246              | 3.245              | 3.246              | 3.246              | 3.246              | 3.246              | 2               |
| B4             | 3.426            | 3.424              | 3.424              | 3.424              | 3.424              | 3.426              | 3.426              | 3.426              | 2               |
| B5             | 3.597            | 3.596              | 3.598              | 3.598              | 3.596              | 3.597              | 3.596              | 3.600              | 3               |
| B6             | 3.813            | 3.813              | 3.814              | 3.815              | 3.815              | 3.813              | 3.813              | 3.814              | 2               |
| B7             | 3.991            | 3.991              | 3.993              | 3.993              | 3.991              | 3.993              | 3.991              | 3.991              | 2               |
| B8             | 4.193            | 4.193              | 4.195              | 4.195              | 4.195              | 4.194              | 4.194              | 4.194              | 2               |
4. System simulation

In order to verify the effectiveness of this method, a simulation experiment was performed in MATLAB’s Simulink. In order to facilitate the calculation of the equalization efficiency, the simulation uses the battery’s SOC (State of Charge) as the equalization condition. A four-cell battery was set up with a rated voltage of 3.7 V and a capacity of 1AH, and set the initial values to 81%, 80.8%, 80.2%, and 80%. The line parameters are: \( L = 10 \, \mu\text{H}, \, C = 2.2 \, \mu\text{F}, \, R = 0.2 \, \Omega \). Under the condition that the battery energy difference is so small, the speed of equalization under traditional switched capacitor equalization method is extremely low or impossible to perform. Therefore, only single-tiered resonance equalization and double-tiered resonance equalization experiments are compared.

The experimental results are shown in Figure 7(a,b). The circuit of the single-tiered resonant equalization module can only transmit energy level by level, so a longer equalization time is used. At 70 s, the energy of the four cells reaches equalization and the efficiency is about 75%. The circuit using the double-tiered resonant equalization module achieves equilibrium around 17 seconds, and the equalization efficiency is about 85%, because it provides more energy transfer paths and increases the voltage of the equalization battery. Therefore, when multi-stage transmit is required, the double-tiered resonant equalization has a higher equalization speed and efficiency than the single-tiered resonant equalization.

5. Experimental test

5.1. Design of voltage acquisition system

The voltage of the battery is an important parameter that reflects the energy of the battery. Under the same conditions, the larger the open circuit voltage of the battery is, the bigger its power is. Therefore, the battery voltage balance can be approximately regarded as the energy balance. At present, the voltage detection methods of the commonly used series battery cells can be divided into distributed and centralized types according to the topology. The distributed architecture is suitable when the number of batteries is small. When the number of batteries is large, a centralized topology can effectively reduce the volume and cost of the circuit. In this paper, a voltage detection circuit of a series lithium-ion battery cell based on a switch array is designed, and the batteries in the battery cell are connected to a high-precision differential amplifier circuit after detection by a switch array controlled by a decoder circuit. This method can effectively suppress common-mode signals between battery cells to achieve high-precision battery detection.

The system block diagram of voltage acquisition circuit design is shown in Figure 8. It mainly includes a battery pack consisting of several sections in series, a switch array controlled by a decoder circuit, a high-precision differential amplifier circuit with a voltage follower circuit and a full-wave precision rectifier circuit, a minimum system circuit is composed of the main control chip STM32 of the built-in 12-bit ADC, a TFT-LCD.
touch screen and host computer display module and auxiliary power supply. The principle is as follows: firstly, the STM32 issues a command to control a certain group of switches in the switch array to be closed by controlling the decoder circuit, and then a battery in the battery pack is connected to a high-precision differential amplifying circuit, and then the STM32 MCU performs A/D conversion, and finally the data is processed and displayed.

In the experiment, selects eight series of batteries are selected as the studying objects, and the discrete distributed voltage values between 2.75 and 4.2 V are selected for testing. The collected data are displayed through TFT–LCD touch screen and upper computer software. At the same time, the actual value of the battery was detected by a high-precision multimeter. Ten test results randomly selected are shown in Table 1.

It can be observed that the maximum error between the actual detection value of the designed voltage acquisition circuit and the detection value of the multimeter is within 3 mV. And by analysing the results of 30 tests of 8 batteries, the probability of errors within 2 mV is about
97.1%. All these show the high accuracy of the detection circuit which meets the voltage detection requirements for the equalization.

5.2. Equilibrium experiment

In order to further verify the equalization method proposed in this paper, a balanced experimental platform as shown in Figure 9(a) was built. A four-cell lithium-ion battery with a 4 AH battery capacity is used in the experiment. The battery has a discharge cut-off voltage of 2.75 V and a charge-limit voltage of 4.2 V. The MOSFET switch adopts the IRF3205 with low conduction resistance and uses an isolated half-bridge driver IC IR2104 for driving. Each battery voltage was sequentially set to 3.30 V, 3.40 V, 3.50 V, 3.60 V by charging and discharging. In order to reduce the voltage fluctuation caused by the battery charging and discharging, the detected voltage is processed by a moving average filter algorithm, and the voltage value obtained after processing is used as an evaluation criterion for three equalization experiments, and then an equalization experiment is performed, and an oscilloscope is used. The capacitor voltage waveforms are observed by an oscilloscope, as shown in Figure 9(b,c).

From the results of the experiments in Figure 10(a,b), the single-tiered resonant equalization four-cell battery reaches equalization around 1100 s, and the equalization voltage of each battery is about 3.44 V. The double-tiered resonant equalization four-cell battery reaches equalization in about 500 s. The equalization voltage of each battery is about 3.45 V. Clearly, the double-tiered resonant equalization improves the battery consistency much faster and more efficiently than single-tiered resonant equalization.

6. Conclusion

In this paper, a double-tiered modular equalization strategy based on the three-resonant-state LC converters is proposed to solve the issue of low equalization efficiency and low speed due to the low voltage difference between batteries and multi-stage transfer at the end of the equalization. The outer modules and inner modules are independent of each other, but can work simultaneously. Compared with the simulation platform of MATLAB and the experimental platform, the experimental results show that the proposed double-tiered modular resonant equalization can effectively improve the equalization speed and efficiency, and can improve the consistency between batteries much faster and more efficiently, thus it has a promising application prospect in the battery tube system.

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