Acta Technica 62 (2017), No. 6B, 225–236 © 2017 Institute of Thermomechanics CAS, v.v.i.

Analyzing the method for measurement and equalization of lithium-ion batteries in electric vehicle

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Abstract. To improve the performance of algorithm for the measurement and equalization control of new lithium-ion batteries of electric vehicle, a kind of equalization control algorithm of single-equalizer lithium-ion battery based on PID algorithm is proposed in the Thesis. Firstly, the energy equalization controldiagram of single-equalizer lithium-ion battery is given and one equalizer is connected with two lithium-ion batteries and PID is used to control the connection and turn-off of MOSFET control switch to realize the energy-balanced optimization of new lithium-ion batteries of electric vehicle; secondly, the equalization controller equivalent circuit with additional output inductance is used to analyze the steady-state characteristic of the proposed single-equalizer lithium-ion battery equalization control algorithm based on PID algorithm; finally, the simulation experiment is conducted to verify the effectiveness of the proposed method on the measurement and equalization control of lithium-ion batteries of electric vehicle.

Key words. Electric vehicle, Lithium-ion batteries, Equalization control, Steady-state characteristic, PID control.

1. Introduction

The power battery technology is a technological bottleneck in the development of electric vehicle[1–4]. For how to make the batteries increase the endurance mileage of vehicles at the same time of ensuring the dynamic property of vehicle, the battery management system is required to conduct the optimal control of battery. The battery management system can lengthen the service life of battery and ensure that the battery can give play to its maximum energy as possible within the effective life cycle[5–7].

At present, the batteries are different from batteries in the past from the early design stage to the use process and the power battery cells are gradually integrated

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into the design and manufacturing process of the complete vehicle. At the early design stage of the complete vehicle, the designer hopes to adopt the high-voltage power system to reduce the operating current and so as to reduce the wire diameter of the wire harness used and it is favorable when considered from the layout and cost of the complete vehicle[8–11]. This one high and one low variation trend causes two obstacles to the battery management system: (1) how to measure as more as possible batteries within shorter time so as to real-timely reflect the real condition of batteries; (2) how to control each battery cell in batteries during the use process to ensure the consistency of the whole group of batteries. The scope of voltage for the charge and discharge of single series of polymer lithium-ion battery is generally 3.0V$\sim$4.2V. Actually, the inflection point of the maximum curvature for the reduction of typical discharge curve is generally about 3.5V. Therefore, the residual battery capacity under this voltage is less than 10%. If the single series of lithium-ion battery is adopted to supply power to the switching power supply circuit with high voltage more than 5V and high power output, the input current will be large and the loss in the transistor and inductance coil in the switching circuit will also be large and the too high output/input voltage ratio makes it hard to achieve the high efficiency and high power output. In general, lithium-ion batteries are used in series to improve the input voltage and reduce the input current, so as to reach certain output power and high efficiency[12-16]. However, lithium-ion batteries in seriesbring about a problem hard to be solved: as there is inconsistency between the capacities of single series of batteries, the battery with the smallest capacity will be saturated to reach 4.2V during the equalization control, thus causing the turn-off of other protection circuits and failure to be fully charged of other series of batteries; during the discharge, the voltage of battery with small capacity will be reduced faster and run out of and other batteries can not work even with residual capacity. The inconsistency between the capacities of series of batteries is mainly due to three aspects: (1) the capacity tolerance during the manufacturing; (2) inconsistent aging rate after a period of use; (3) different automatic discharge speed of different series during the lay-down period after equalization control. Therefore, the capacity equalization between series of lithium-ion batteries is necessary. At present, there are some researches and reports on equalization circuit. The equalization circuit keeps the voltage deviation between series of batteries within small range to prevent the gradual differentiation of voltage and increase the actual output capacity or service life of the whole batteries.

The PID lithium-ion battery equalization control algorithm is proposed in the thesis and the algorithm does not require a complex control algorithm to eliminate components of resonance. The transfer function from control to output contains the equivalent circuit model of lithium polymer battery. Different from the traditional equalization controller, the PI controller is used to control the output current and voltage to realize the constant current (CC) and constant voltage (CV) equalization control model. The experimental results verify the feasibility and effectiveness of equalization controller and its control method.

2. Lithium-ion battery equalization control circuit

2.1. *Voltage sampling*

The model of lithium-ion battery equalization includes simple energy consumption equalization and energy transfer equalization and energy conversion equalization which are widely studied at present: the two-way lossless equalization method modified based on capacitance equalization can realize equalization but requires huge number of elements with the increase of number of batteries in the battery pack and the energy transfer is achieved through capacitor and it has high requirements for the quality of capacitor; secondary equalization method can obtain high voltageconsistency but the circuit and control method are complex and the cost is high and a large quantity of energy losses are produced during the first equalization; for the method in which the inductance serves as stored energy to realize the equalization, the efficiency to transfer energy of inductance is too low; capacitor switching method requires many switching elements and lacks monitoring and the capacitor may produce energy which is released and the battery may charge the capacitor and the capacitor is likely to explore during the energy transfer between capacitor and battery; transformer equalization method: the method can realize quick equalization, but when the number of batteries increases or decreases, the transformer must be designed again and the expansion change is inconvenient.

If the electric quantity equalization is not adopted for series batteries, the series with low capacity may reach saturation in advance in the charge process or the voltage may be too low in the discharge process and may be switched off due to the overcharge/over-discharge prevention function of protection circuit and the service life may be influenced as the lithium-ion battery reaches the protection voltage every time during the working. Therefore, it is necessary to conduct real-time monitoring and comparison for the voltage of various series of lithium-ion batteries. In case the voltage of a certain series of batteries is found to be low, it shall be controlled by single chip microcomputer (MCU) and charged through equalization circuit. MCU setting is as follows: when the voltage of any series of batteries is less than 3.5V, the power supply will be stopped; therefore, it is unnecessary to consider whether the single series of batteries are overcharged or over-discharged. As the scope of voltage sampling of analog-digital converterADC is $0 \sim 5$ V, the sampling of component voltage shall be conducted for more than one series of grounded battery voltage so as to obtain the voltage of 2 series and 3 series of batteries in accordance with the proportion and then obtain the voltage of each single series of batteries. The voltage sampling circuit adopted is as shown in Fig.1.

In Fig.1, the voltage obtained through sampling at IN0 port is the voltage of the first series of batteries, the voltage obtained through sampling at IN1 port is 1/2 of the sum of voltages of the first series of batteries and the second series of batteries and the voltage obtained through sampling at IN2 port is 1/3 of the sum of voltages of the three series of batteries. Assume that the voltages of the three series of batteries are respectively V_{B1}, $V_{B2}$and V_{B3} and the input voltages at ports IN0, IN1 and IN2 are respectively $V_{[0]}$, $V_{[1]}$ and $V_{[2]}$, then the voltages at both ends

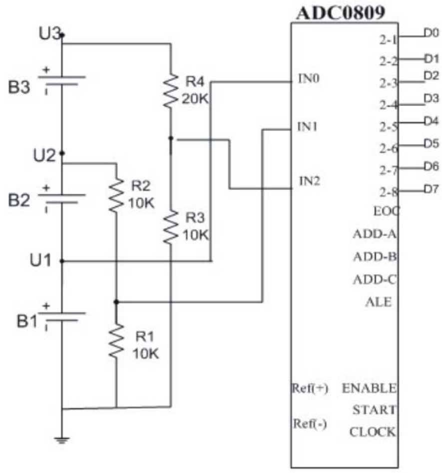


Fig. 1. Voltage sampling circuit

of battery are respectively:

$$V_{B1} = V_{[0]} , \tag{1}$$

$$V_{B2} = U_2 - U_1 = 2 \times V_{[1]} - V_{[0]} , \tag{2}$$

$$V_{B3} = U_3 - U_2 = 3 \times V_{[2]} - 2 \times V_{[1]} . \tag{3}$$

The resolution ratio of AD0809 is $\delta = 5/2^8 \approx 0.02V$. To improve the accuracy of measurement, the Single Chip Microcomputer conduct 10 times of continuous sampling for the voltage of each battery and obtain the average value and make comparison between battery voltage with the above-mentioned algorithm.

2.2. Energy equalization control of single-equalizer lithium-ion battery

Fig.2 is the energy equalization control diagram of single-equalizer lithium-ion battery in which one equalizer is connected with two lithium-ion batteries and energy equalization optimization control is conducted based on PID.

The control loop of single-equalizer lithium-ion battery includes two groups of inductance $L1$ and $L2$ with coupling relation, the capacitor in the loop is $C1$, $D1$ and $D2$ are diode modules, $Q1$ and $Q2$ are two MOSFET modules which serve as control switch to realize the equalization control of the lithium-ion battery equalization control process. Two groups of series batteries make use of capacitor $C1$ to realize the automatic transfer of unbalanced energy which can be effectively controlled based on the connection and turn-off time of the MOSFET control switch.

It is assumed that T_s refers to control cycle and D refers to loop duty cycle, and initial voltage value of V_{C1} is set as $V_{B1} + V_{B2}$; if $V_{B1} > V_{B2}$, then $Q1$ switch is

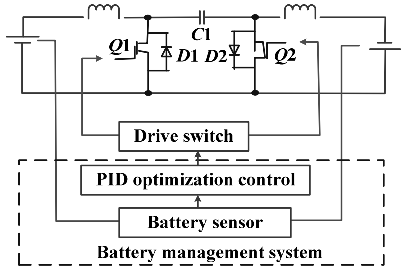
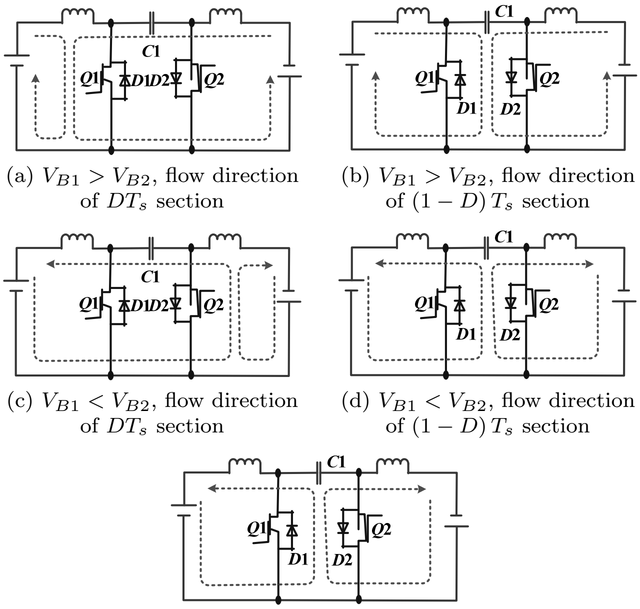


Fig. 2. Energy equalization control diagram of single-equalizer lithium-ion battery



(a) $V_{B1} > V_{B2}$, flow direction of DT_s section

(b) $V_{B1} > V_{B2}$, flow direction of $(1-D)\,T_s$ section

(c) $V_{B1} < V_{B2}$, flow direction of DT_s section

(d) $V_{B1} < V_{B2}$, flow direction of $(1-D)\,T_s$ section

(e) $V_{B1} > V_{B2}$ Oscillogram

Fig. 3. Flow situation of current

turned on during DT_s period. It is shown in Fig. 3a that buffer energy in capacitor $C1$ passes through $L2$ and V_{B2} with current, and transferred to V_{B2}, meanwhile, $L2$ can be used to store energy in V_{B1} and transferred to inductor $L1$. As shown in Figure 3e, energy storage is always carried out in the inductor $L1$ and $L2$ during DT_s of the control process, and the storage current increases. As shown in Figure 3b, during $(1-D)\,T_s$ of control process, when $Q1$ is switched off, $D2$ will be opened at the same time, and energy inside V_{B1} and $L1$ will be transferred to capacitance in the form of current, while the energy in $L2$ will be controlled with equalization of lithium battery V_{B2}. As a result, the current between $L1$ and $L2$ during $(1-D)\,T_s$ of control process will continue to decrease. The above process is to transfer control loop energy on the premise of $V_{B1} > V_{B2}$; for $V_{B1} < V_{B2}$, the control process is similar, as shown in Fig. 3c-d. For $V_{B1} < V_{B2}$, the energy transfer process is mainly controlled through $Q2$. At the moment, energy of equalization control is transferred from V_{B2} to V_{B1}.

If $V_{B1} > V_{B2}$, then $Q1$ will be opened during DT_s period $(t_0 \leq t < t_1)$,

$$V_{B1} = L1\frac{di_{L1}}{dt}, i_{L1}(t_0) = I_0\,, \tag{4}$$

$$V_{B2} = -L2\frac{di_{L2}}{dt} + \frac{1}{C1}\int i_{L2}dt, i_{L2}(t_0) = I_0, V_{C1}(t_0) = V_{B1} + V_{B2}\,. \tag{5}$$

If $Q1$ is closed, then $D2$ will be opened, namely during $(1-D)\,T_s(t_1 \leq t < t_2)$:

$$V_{B1} = L1\frac{di_{L1}}{dt} + \frac{1}{C1}\int i_{L1}dt, i_{L1}(t_1) = I_P, V_{C1}(t_1) = V_{B1} + V_{B2}\,, \tag{6}$$

$$V_{B2} = -L2\frac{di_{L2}}{dt}, i_{L2}(t_1) = I_P\,. \tag{7}$$

Under steady-state equalization control, current transmission mean of buffer capacitor $C1$ is as follows:

$$i_{L1}(1-D)T_s - i_{L2}DT_s = 0\,, \tag{8}$$

If T_s refers to control cycle; D refers to duty cycle of control loop, then it can be got that:

$$I_{L1} = [\frac{1}{2}(\frac{V_{B1}}{L1}D^2 + \frac{V_{C1} - V_{B1}}{L1}(1-D)^2)]T_s\,, \tag{9}$$

$$I_{L2} = [\frac{1}{2}(\frac{V_{C1} - V_{B2}}{L2}D^2 + \frac{V_{B2}}{L2}(1-D)^2)]T_s\,. \tag{10}$$

According the Equation (9-10), current makes great influence on the switching cycle T_s. Therefore, equalization control effect can be obtained through cycle control of loop switch.

3. Steady-state characteristics of equalization controller

Equivalent circuit of equalization controller with additional output inductor as shown in Fig. 4 can be controlled by switch ON/OFF. In this circuit, only the simplified analysis of lithium polymer battery and output capacitor of the Equivalent Series Resistance (ESR) is considered because equivalent resistance of the other elements is small and does not affect operation of the circuit. It is well known that the input inductor must be designed based on desired current value of new lithium battery stack of protonelectric vehicle of desired output ripple. To limit the output current ripple of fuel cell within a certain interval, the minimum inductance required can be calculated as:

$$L = \frac{V_s D}{I_L \Delta i_L^{\%} f_s}\,. \tag{11}$$

In addition, the relationship between voltage ripple of output capacitor can be obtained by circuit analysis:

$$\Delta v_c = \frac{(V_0 - V_{C_b})D}{CR_b f_S} + (I_L + \frac{\Delta i_L}{2})R_c\,. \tag{12}$$

According to Equation (12), it can be noted that the output voltage ripple can be controlled by a shunt capacitor because it is proportional to the ESR of the capacitor and is inversely proportional to the capacitance. Since the first item on the right side of Equation (12) is less than the second item, the output voltage ripple depends primarily on the ESR value of the capacitor. Therefore, in order to meet the requirements of 0.5% (63 mV) of output voltage ripple, ESR of the output capacitor must be much smaller than 4.2mΩ because when the fuel cell stack provides maximum output power with minimum output power of 6V, the maximum average current of front end inductance (L) can be calculated as 15A. The minimum ESR value of commercially available electrolytic capacitor is 49mΩ and the capacitance is 1000μF. Therefore, in order to meet the requirements of output ripple, at least 12 capacitors are required in parallel, which will result in need of additional cumbersome converters.

In the equalization controller, an additional inductor is used between the output capacitor and the battery to reduce size and cost of the output filter, as shown in Fig.4. In the converter with additional output inductor, it is necessary to connect only three shunt capacitors in consideration of the rated value of ripple current of the previously selected capacitor (2.25 A) because the root-mean-square ripple current of the output capacitor can be calculated as 6.3 A, in the form of :

$$I_{C(RMS)} = I_o\sqrt{\frac{D}{1-D}}\,. \tag{13}$$

The output inductance plays an important role in meeting requirements of output ripple of the equalization controller. The specific design process is as follows:

$$\Delta v_0 = \Delta i_o R_b\,, \tag{14}$$

$$\Delta v_0^{\%} = \Delta i_0^{\%}(1 - \frac{V_{C_b}}{V_0})\,. \tag{15}$$

In consideration of the large capacitance in equivalent circuit model of battery, the relationship between output voltage ripple and output current ripple can be derived as Form (14-15). By using Kirchhoff Voltage Law (KVL), voltage on output capacitor can be expressed as:

$$v_c(t) = v_o(t) + v_{L_o}(t)\,. \tag{16}$$

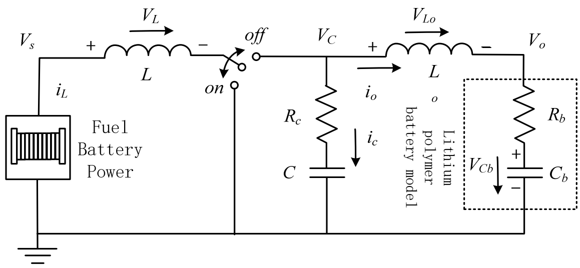


Fig. 4. Equivalent circuit of equalization controller

During the switching time period, size of the ripple can be expressed as

$$L_o \frac{\Delta i_o}{DT_s} + \Delta v_o = \Delta v_c\,. \tag{17}$$

Therefore, in order to meet limit of output voltage ripple and output current ripple, the required output inductance can be calculated as:

$$L_o = \frac{(\Delta v_c - \Delta v_o)D}{\Delta i_o f_s}\,. \tag{18}$$

4. Experimental analysis

Specification of equalization controller for fuel cell used for calculation in the above equation and parameters of all converters are set as follows: rated power of 90W, input voltage V_S = 6-10V, equalization control voltage V_o = 12.6V, equalization control currentI_o = 6A, switching frequency f_S = 300kHz,input inductance L = 45μA, output inductance L_o = 0.7μH, output capacitance C = 3000μF, battery resistance R_b = 0.116Ω, battery capacitance C_b = 21500F, output voltage ripple Δv_o = 63mV (5%), output current ripple Δi_o = 60mA (5%), PEMFC output current ripple Δi_L = 300mA (2.5%).

Experimental connection diagram used in the process of simulation experiment is shown in Fig. 5; the following devices are used for the connection diagram in this figure: ① electrical signal measuring device (voltmeter, ammeter), ② lithium polymer battery, ③vMax745 IC external PI controller, ④vvoltage controller, ⑤ current controller, ⑥vfuel cell, ⑦ PWM logic generator.

Firstly, equalization control experiment should be carried out for new lithium battery stack of proton electric vehicle to test switching effect of equalization control model during the experiment. The experimental results of equalization control curve for equalization controller of lithium polymer battery are shown in Fig. 8.

Current value of configuration file of equalization control model for lithium polymer battery shown in Fig. 6 is 6A (0.5C); equalization control voltage is 12.6V, and new lithium battery stack of the proton electric vehicle operates under model

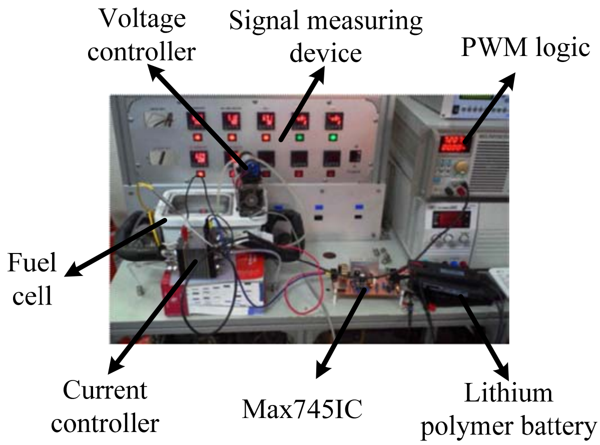


Fig. 5. Experimental facility of equalization controller

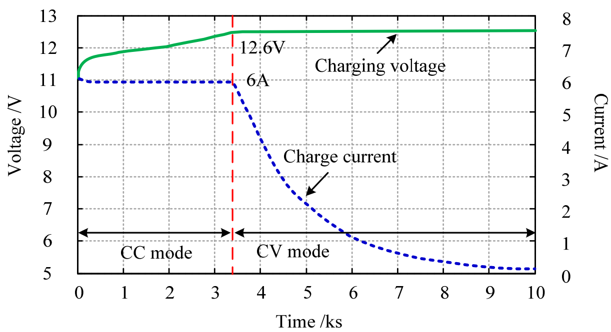


Fig. 6. Switch of equalization control model of equalization controller

1. Equalization controller operates well and it takes about 3 hours to change the battery from full discharge state to full equalization control state. When current of equalization control battery pack is reduced to 0.24 A (0.02 C), the equalization control process is completed.

Dynamic characteristic of equalization controller when output current load is applied to equalization controller in CV model is shown in Fig. 7.

Dynamic characteristic of equalization controller with 12A load during operation in mode 1 (equalization control in CV mode) is shown in Fig. 7. At the beginning of equalization control, equalization control of battery is in CC mode, followed by CV mode. At t_1 time, when 12A current load is applied to the system, the battery is in CV equalization control mode. In this case, operation switch is switched from mode 1 to mode 4. At the same time, for limit value of equalization control output current is6A, the battery is discharged with6A to achieve power supply for 12A load.

Current control curve in the process of equalization control of lithium battery with the control algorithm in the thesis is shown in Fig.8, and the voltage curve at the end point of control equalization and equalization is shown in Figs. 7b-c.

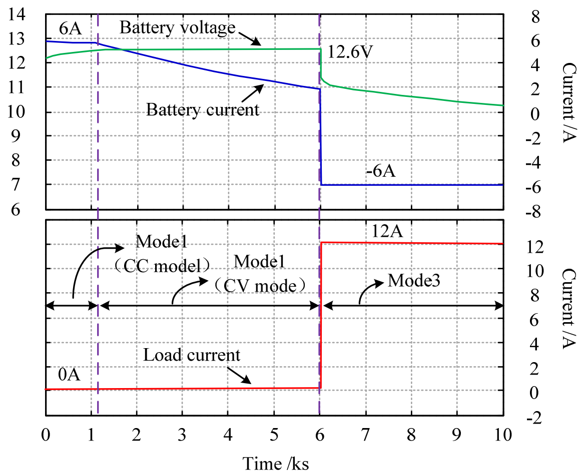
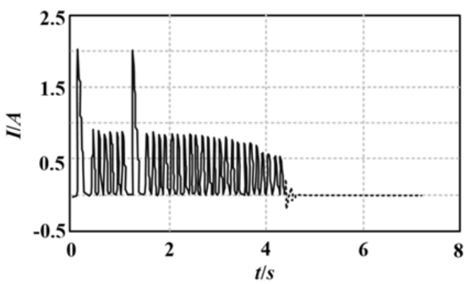
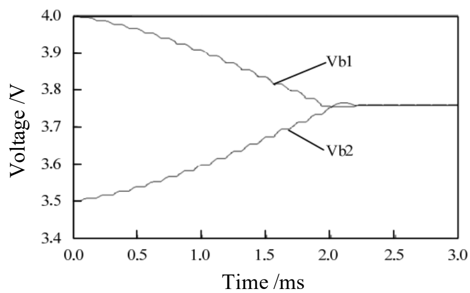


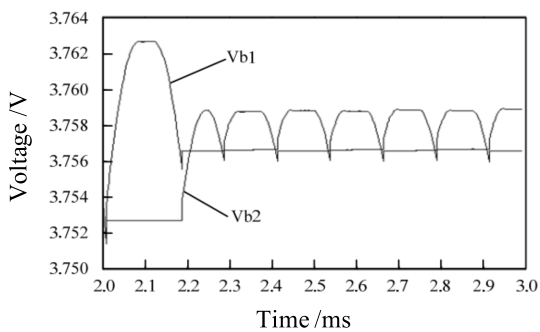
Fig. 7. Dynamic characteristic of equalization controller



(a) Result of current simulation



(b) Equalization voltage curve



(c) Voltage curve at the end point of equalization

Fig. 8. Equalization control curve

It can be seen from curve of Fig. 8a that when the proposed control method is used to carry out equalization control for current, current value at the starting node is large. However, with the equalization control process, the current in control circuit is gradually reduced and eventually tends to zero. According to experimental results in Fig. 7b-c, it can be seen that PID optimal and tuning control method proposed in this thesis can effectively solve the problems that control accuracy of lithium battery in the process of equalization control is not high and oscillation exists, which is beneficial to reduce energy loss and then obtain ideal equalization control performance, and access to more efficient equalization control performance of lithium battery.

The battery is new factory one before test, so initial voltage of each battery in battery pack is set for three kinds of imbalance states respectively, and then corresponding equalization control method should be used until error of the entire battery pack reaches 30mV or less, and equalization stops. Voltage value of battery pack before and after equalization is shown in Table 1.

Table 1. Voltage value of single cell battery before and after equalization

State	Before and after equalization	U_{B1}/V	U_{B2}/V	U_{B3}/V	U_{B4}/V	U_{B5}/V	U_{B6}/V
1	Before	3.7	3.71	3.687	3.86	3.693	3.706
	After	3.707	3.716	3.694	3.724	3.7	3.713
2	Before	3.707	3.684	3.525	3.693	3.689	3.697
	After	3.688	3.667	3.658	3.675	3.671	3.679
3	Before	3.707	3.61	3.71	3.9	3.694	3.702
	After	3.707	3.69	3.71	3.72	3.694	3.702

It can be seen from analysis of the test data that the results obtained are basically the same as theoretical results, and the equalization effect is obvious. Due to energy consumption in the circuit, energy released from the battery or battery pack with higher voltage is more than that with lower voltage. Therefore, change of voltage of battery or battery pack with high voltage is relatively faster.

5. Conclusion

An equalization control algorithm of single-equalizer lithium-ion battery based on PID algorithm is proposed and equalization control diagram of single-equalizer lithium-ion battery is provided in this Thesis to control On/Off of MOSFET control switch combing with PID and analyze steady-state characteristics of equalization control algorithm for single-equalizer lithium-ion battery based on PID algorithm. The results show that the proposed method is effective and can be used to guide actual design of the charger.

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Received May 7, 2017