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A Novel Active Cell Balancing Circuit and Charging Strategy in Lithium Battery Pack

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Received: 18 October 2019; Accepted: 20 November 2019; Published: 24 November 2019

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Abstract: A novel, active cell balancing circuit and charging strategy in lithium battery pack is proposed in this paper. The active cell balancing circuit mainly consists of a battery voltage measurement circuit and switch control circuit. First, all individual cell voltages are measured by an MSP430 microcontroller equipped with an isolation circuit and a filter circuit. Then, the maximum cell voltage difference is calculated by subtracting the minimum cell voltage from the maximum cell voltage. When the maximum cell voltage difference exceeds 0.05 V, the balancing action starts to carry on. The MSP430 microcontroller output controls signals to close the switches corresponding to the battery cell with the maximum voltage. At this time, the balancing charge power performs a balancing charge for other batteries, except for the one that is switched on. In addition, a three-stage balancing charge strategy is also proposed in this paper to achieve the goal of speedy charging with balancing action. In the first stage, a 0.5 C balancing current is used to perform pre-balanced charging on all battery cells until the maximum cell voltage difference is less than 0.05 V, which is required for entry to the second stage of charging. In the second stage, constant current charging of 1 C, coupled with 0.2 C balancing current charging is carried out, until the maximum battery cell voltage reaches 4.2 V, which is required for entry into the third stage of charging. In the third stage, a constant voltage charging is coupled with 0.2 C balancing current charging, until the maximum battery cell voltage reaches 4.25 V, which is required to complete the balancing charge. The imbalance of power between the battery cells during battery pack charging, which reduces battery charging efficiency and battery life, is thus effectively improved. In this paper, a six-cells-in-series and two-in parallel lithium battery pack is used to perform a balancing charge test. Test results show that the battery cells in the battery pack are capable of quickly completing a balancing charge under different initial voltages, the maximum voltage difference is reduced to within the range of 0.05 V, and the total time required for each balancing charge is approximately 3600 s.

Keywords: lithium battery pack; cell balancing circuit; switch control circuit; three-stage balancing charge strategy

1. Introduction

The extensive use of fossil energy by humans has a great impact on the environment. Not only do the traditional steam locomotives consume a lot of oil resources but the exhaust gas emitted is also one of the main causes of the greenhouse effect. Therefore, finding a way to save energy and reduce carbon has been the topic of discussion in various countries [1,2]. In response to the environmental protection policies in different countries, electric vehicles powered by electricity have flourished. Secondary batteries are the key energy storage components for electric vehicles. Secondary batteries have wide applications. With the wide applications of secondary batteries and the advancement of electronic technology, the performance of batteries has also attracted a lot of attention. Currently, the most common secondary battery is a lithium battery, because of its high working voltage, high energy density, absence of memory effect, low self-discharge rate, long life, etc. [3,4]. In order to meet the high power demand, lithium batteries usually increase the battery pack voltage and capacity through series–parallel connection. However, due to the varied battery charging and discharging characteristics and aging, power imbalance between batteries might result, thereby, reducing battery charging and discharging efficiency and seriously affecting battery life. Hence, battery balance is indispensable [5–16]. Many research literature have proposed a variety of balancing charging techniques, such as the resistive balancing method, the capacitive balancing method, the inductive balancing method, the transformer balancing method, and the power converter balancing method. However, the resistive balancing method uses one resistor at both ends of the battery for circuit balance purpose. When the charger is charging and the battery voltage reaches a certain value, the switch is turned on, which discharges excessive energy through a resistor to balance the battery voltage. The capacitive balancing method uses a capacitor to transfer energy. Each capacitor is connected to two batteries through the switch. Through the action of the switch, excessive energy can be converted between the batteries to achieve voltage balance. The inductive balancing method is made up of two switches and one inductor, which are used to transfer energy. Through the switching of the switch, the battery energy with a higher voltage is stored in the inductor, and the energy in the inductor is transferred to another battery with a lower voltage. The transformer balancing method performs energy transfer at the battery pack end through winding to achieve voltage balance. The transformer's winding can store energy in the battery or battery pack and transfer the energy to the necessary battery [17–24]. The power converter balancing method transfers energy between power and batteries through voltage increases and decreases, combined with the use of the switch [25–29]. The above battery balancing methods come with various disadvantages, such as a complex circuit structure, loss caused by circuit actions, and excessive components [30–33].

This paper proposes a new lithium battery pack active cell balancing circuit and a three-stage charging strategy. The charging process is divided into three stages. The first stage is the pre-balancing stage, with a balancing current of 0.5 C. The balancing circuit will measure the voltage of each cell and calculate the maximum voltage difference between batteries. When the maximum voltage difference exceeds the set value of 0.05 V, the circuit will commence the balancing action and open the switch corresponding to the battery with maximum voltage. At this time, the balancing charging circuit will commence balancing charging on other batteries until the maximum voltage difference range of the battery is less than 0.05 V. At this point, the circuit balancing is considered to be complete. The second stage is the main charging stage, with a charging current of 1 C. At this time, the balancing current decreases to 0.2 C, and the circuit commences constant current charging on all batteries. At the same time, the voltage differences among all batteries continue to be measured. When the maximum voltage difference exceeds 0.05 V, the circuit performs balancing charging action on the batteries. When the battery with the maximum voltage is charged to 4.2 V, the charging power enters the third stage, the constant voltage charging stage, until the battery with the maximum voltage reaches 4.25 V and the charging shuts down to complete the entire charging process. The charging strategy proposed in this study is different from the traditional CC–CV charging strategy in the main charging stage to the second stage. In this paper, in addition to the main charging current a balance current was also used, which allows reduces the balance charging time [34]. In this study, the six in-series and two in-parallel lithium battery pack was used to carry out the actual balancing charging test. The test results showed that the respective battery cells in the battery pack could reduce the maximum voltage to within the 0.05 V range, under different initial maximum voltage differences, with a balancing charging time of approximately 3600 s.

2. Structure of Active Cell Balancing Circuits

The active cell balancing circuit of the lithium battery pack is shown in Figure 1, which is mainly composed of two parts, namely, the charging circuit and the balancing charging circuit. The circuits include a power supply, a switch circuit, a battery pack, a battery voltage measuring circuit, and a MSP430 microcontroller. The battery voltage measuring circuit consists of an INA128 isolation circuit, a low-pass filter and a reversing amplifier. The measured voltage signal passes through the MSP430 microcontroller to control the switch control circuit.

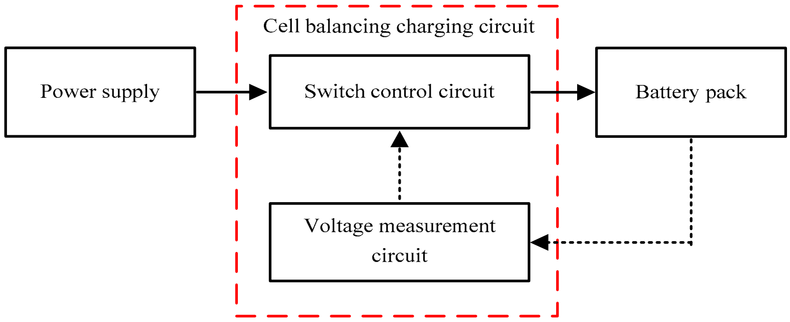

Figure 1. Active cell balancing circuit structure for a lithium-battery pack.

2.1. Charging Circuit of a Lithium-Battery Pack

Figure 2 shows the charging circuit of a lithium-battery pack. The MSP430 microcontroller sends the control signal to the main switch. When the main switch is ON, the power supply provides the charging current to the battery pack for charging. At this time, the battery pack begins charging. When the main switch is OFF, the power supply is turned off and the battery pack charging is completed.

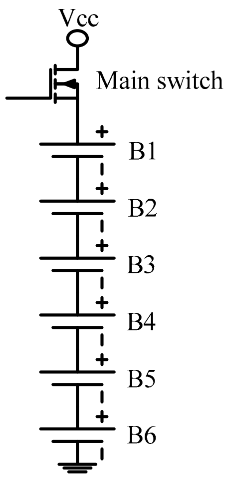

Figure 2. Charging circuit of a lithium-battery pack.

2.2. Balancing the Charging Circuit of a Lithium-Battery Pack

Figure 3 shows the balancing charging circuit of a lithium-battery pack. This circuit carries out the balancing charging on the battery through the MSP430 microcontroller that controls the switch. First, the battery voltage measurement circuit measures the voltage of each battery cell. After computing and determining that balancing is required, the MSP430 microcontroller sends control signals to the corresponding switches and the bypass loop of the corresponding battery is opened. When the switch is ON, both power supplies provide charging current to the corresponding battery to charge. At this time, the battery starts balancing the charge. When the switch is OFF, both power supplies are turned off. At this time, the battery pack balancing is completed.

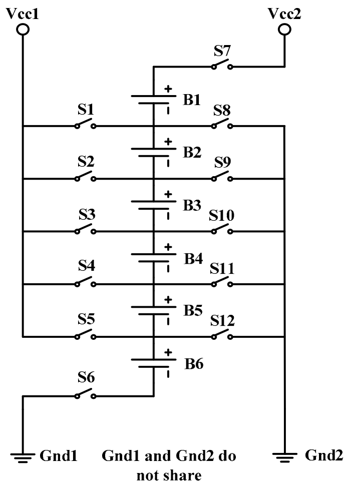

Figure 3. Balancing the charging circuit of a lithium-battery pack.

The battery voltage measurement circuit, switch circuit, and the lithium-battery pack in the lithium-battery pack balancing charge circuit are detailed below.

2.2.1. Battery Voltage Measurement Circuit

Figure 4 shows the battery voltage measurement circuit designed in this paper. This circuit consists of three parts—the instrumentation amplifier isolation circuit, the low-pass filter circuit, and the inverting amplifier circuit. Through the instrumentation, the amplifier's infinite input impedance feature, the output terminal is isolated. In order to prevent the battery from external noise interference during the measurement process and causing the signals to be unstable, the low-pass filter is connected at the back to filter the high-frequency noise. The A/D conversion input of the MSP430 microcontroller used here has a maximum voltage of 3.3 V. Since the battery voltage range is 2 V–4.2 V, the inverting amplifier is needed to attenuate the input signal to the limited input range and to then send it to the A/D converter of the MSP430 microcontroller. Through program computing, balancing the charging control is carried out on the battery. Each parallel battery is complemented by a voltage measurement circuit to carry out the measurement. The battery pack model used in this paper is also conjunctively used. Six voltage measurement circuits are used to perform the measurement and control.

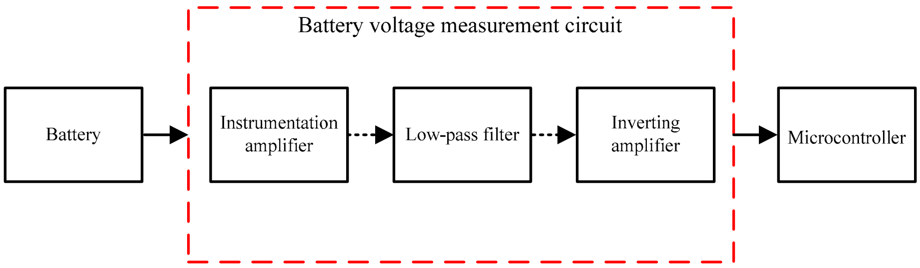

Figure 4. Battery voltage measurement circuit structure.

2.2.2. Switch Circuit

Figure 5 shows the switch circuit proposed in this study. A TLP3543 optical coupling relay is used as a balancing switch. This IC is composed of two MOSFETs, and the MOSFET is turned on by an internal light-emitting diode. The six-series and two-parallel battery pack is used in this paper to perform actual the charging and balancing charging tests. A total of 13 switches are used for switching. When the number of parallel batteries increases in the future, the total number of switches of the proposed switch circuit will not increase.

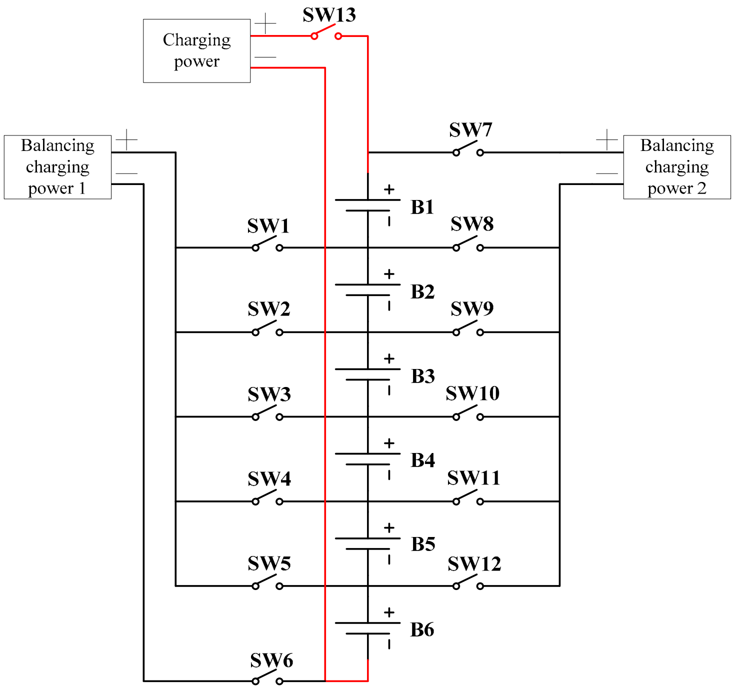

Figure 5. The switch circuit.

2.2.3. Lithium-Battery Pack

The battery pack used in this study is a lithium battery IBR18650BC manufactured by E-ONE MOLI ENERGY CORP. The specifications are shown in Table 1. The capacity of a single battery is 1500 mAh, the rated voltage is 3.6 V, the maximum charging voltage is 4.2 V, the minimum discharge voltage is 2 V, the maximum charging current is less than 9 A, and the maximum discharge current is 30 A. The battery module in the balanced charging mode proposed in this paper uses 12 IBR18650BC to form six series and two parallel lithium battery modules. Since the batteries in parallel have an equal voltage, only one series of battery cell needs to be measured to represent the voltage of the two parallel batteries.

Table 1. Specifications of the lithium battery IBR18650BC.

Shape/Can Material	Cylindrical/Steel
Typical Capacity	1500 mAh
Minimum Capacity	1400 mAh
Nominal Voltage	3.6 V
Charge Voltage	4.2 V ± 0.05 V
Charge Current	Less than 9 A
Charge Time	1.5 h
Discharge current (Max.)	30 A
Discharge Cutoff Voltage	2.0 V

3. The Experimental Processes

This study proposes a new three-stage active cell balancing charge strategy of lithium battery. The charging process is mainly divided into three stages. The overall flowchart is shown in Figure 6.

The balancing charging method in this study involves the usage of 13 switches, including a battery-pack charging and a balancing charging. The switching action states corresponding to the imbalance states are summarized in Table 2. As shown in Table 2, the relationship between each switch action of the seven imbalance states proposed in this paper is mainly related to all switch actions in different states.

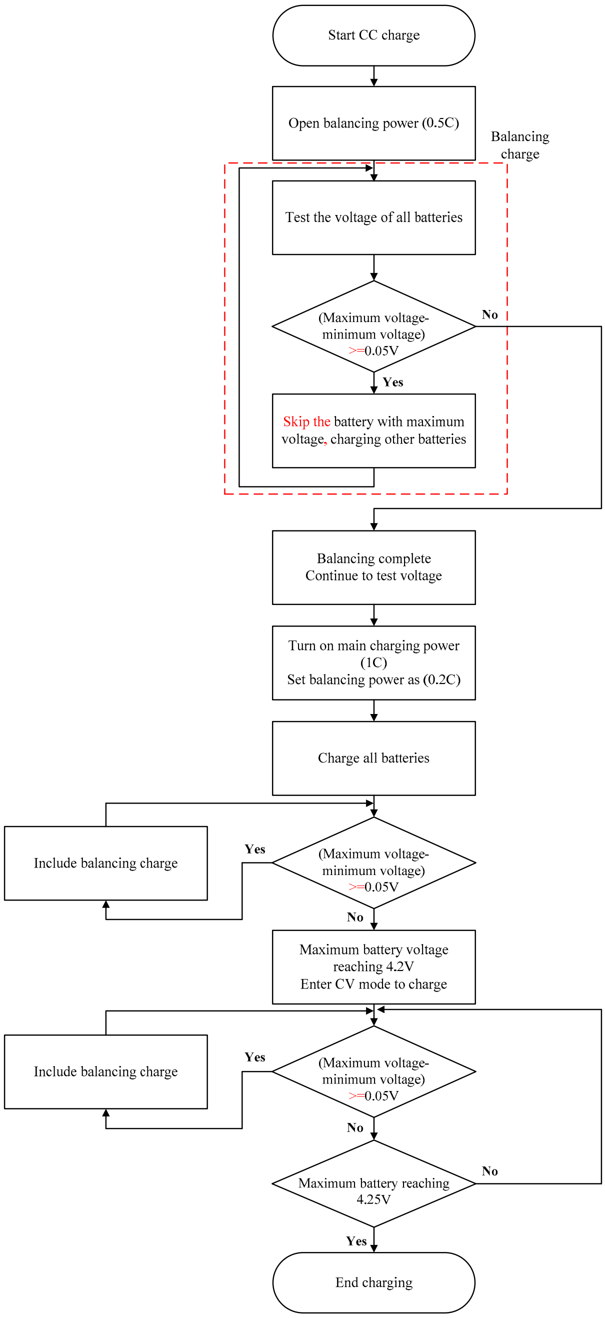

Figure 6. Overall flowchart of three-stage active cell balancing charge strategy.

Table 2. Switching action situations of the different battery imbalance states.

State	Situation	Switching Action State (1 Represents ON; 0 Represents OFF)											
		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
1	The maximum voltage difference is less than 0.05 V.	0	0	0	0	0	0	0	0	0	0	0	0
2	Battery 1 has the maximum voltage.	1	0	0	0	0	1	0	0	0	0	0	0
3	Battery 2 has the maximum voltage.	0	1	0	0	0	1	1	1	0	0	0	0
4	Battery 3 has the maximum voltage.	0	0	1	0	0	1	1	0	1	0	0	0
5	Battery 4 has the maximum voltage.	0	0	0	1	0	1	1	0	0	1	0	0
6	Battery 5 has the maximum voltage.	0	0	0	0	1	1	1	0	0	0	1	0
7	Battery 6 has the maximum voltage.	0	0	0	0	0	0	1	0	0	0	0	1

Then, the charging method of the battery pack balancing charging structure in this paper involves the use of a constant current (CC) and a constant voltage (CV) charging. This charging method is a two-stage charging. In the first stage, constant current charging is adopted. When the battery voltage is low, a higher current is delivered to charge, in order to reduce the overall charging time. However, when the battery voltage rises to the rated voltage, in order to prevent overcharging and ensure that the current is actually charged into the battery, it is necessary to convert into the second stage of constant voltage charging. At this time, the charging current will gradually decrease with time, until the current approaches zero. Although this method can almost fully charge the battery, the current under CV charging is very small, and the charging time is almost twice or three times that of CC charging, thus, the lengthy overall charging time. Therefore, in order to reduce the overall charging time, this study made slight adjustments to the CC–CV charging method, with the CV transition condition being set in the battery, with the maximum voltage reaching 4.2 V, until the battery with the maximum voltage reaches 4.25 V to turn off the power supply. At this time, charging is said to be completed. Figure 7 shows the overall flowchart of the charging action.

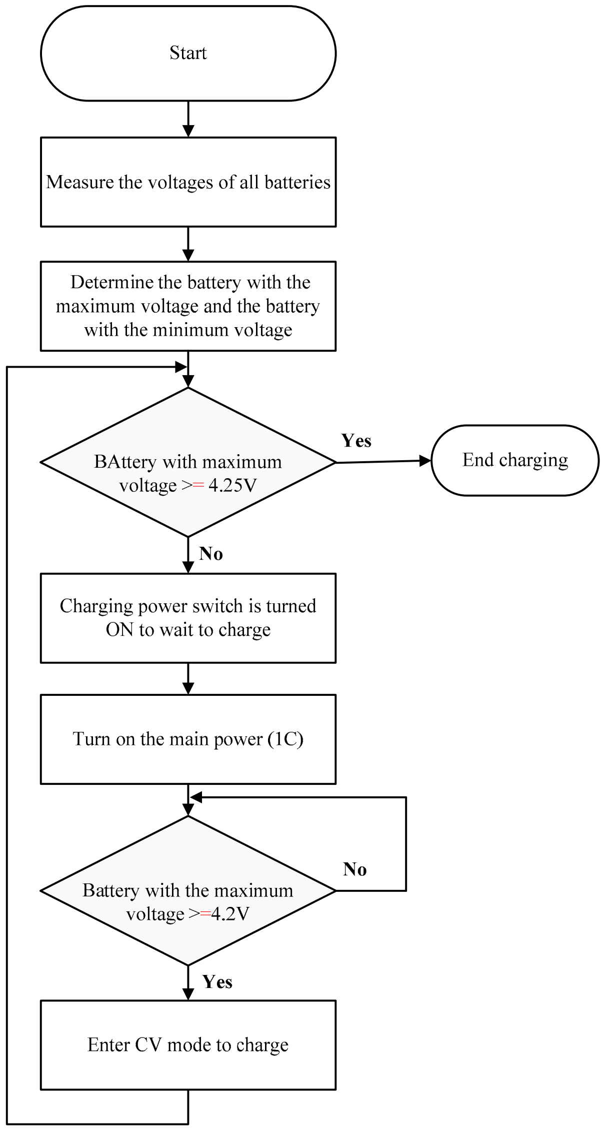

Figure 7. Overall flowchart of the charging action.

The balancing charging method utilizes CC to charge. This charging method charges batteries through fixed small currents. To adjust the current size, an external charging power (power converter) is needed to control the charging current size. In this study, two constant current power supplies are used to provide the balancing charging power. The switch circuit performs charging on different quantities of batteries, according to different imbalance situations. The voltage at the power terminal provides a fixed current based on the voltage of the battery. Although the balancing circuit cannot enable the battery to reach a stable voltage by constant voltage charging, it can perform rapid balancing on the battery pack when multiple batteries have lower voltages. Figure 8 shows the overall flowchart of the balancing charging action.

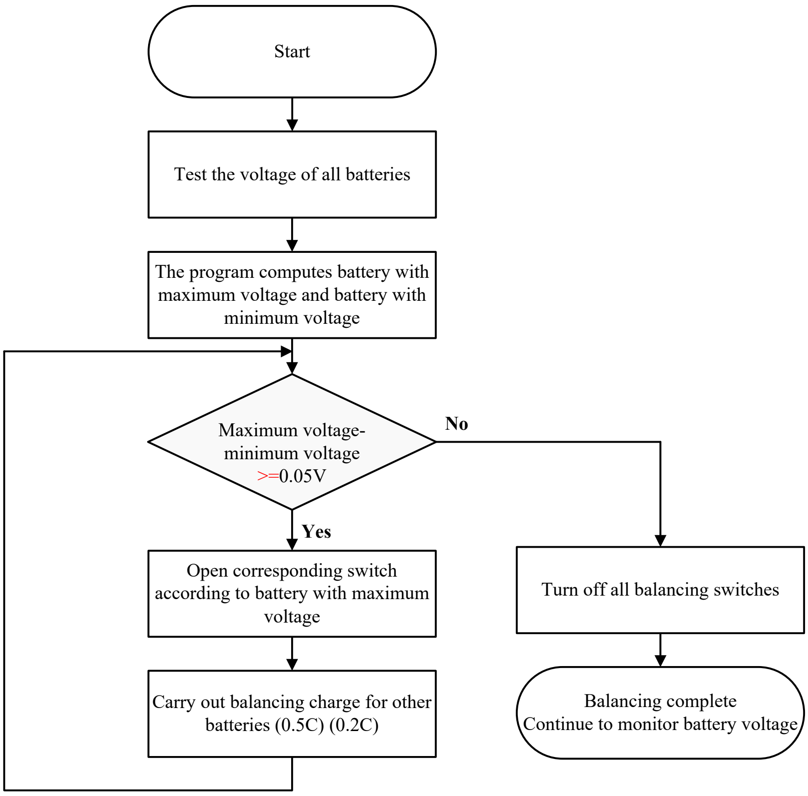

Figure 8. The overall flowchart of the balancing charging action.

4. Testing Results and Discussions

In the balancing charge testing, there were four balancing conditions to be analyzed and discussed, which were the first-stage, pre-balancing current value, second-stage, balancing current value, CC–CV transition condition, and the cut-off of charging. For each condition, three parameters were selected to carry out and compare. At the beginning of the measurement, the charging was turned on after a 30 s interval, and the final maximum voltage difference was observed by standing for 10 min after the completion of charging. The selection of balancing charge conditions for testing are tabled in Table 3.

Table 3. Selection of the balancing charging conditions for testing.

First-Stage Pre-Balancing	Second-Stage Balancing	CC–CV Transition Condition	Cut-Off Condition
1 C	1 C	Maximum battery voltage 4.2 V	Maximum battery voltage 4.25 V
0.5 C	0.5 C	Maximum battery voltage 4.15 V	Maximum battery voltage 4.2 V
0.2 C	0.2 C	Maximum battery voltage 4.1 V	Maximum battery voltage 4.15 V

4.1. First-Stage Pre-Balancing Current Value Analysis

Figure 9 shows the actual test results of the first-stage balancing charging using 1 C balancing current. There were four steps in the balanced charging experiment at this stage. Step 1 was pre-balancing, with 1 C charging; Step 2 was balancing, with 0.2 C charging; Step 3 was the CV stage, with the maximum battery voltage reaching 4.2 V transition; Step 4 was the rest stage where the maximum battery voltage reached 4.25; the battery was then turned off and was in the rest stage for 10 min. Under the initial state, the maximum voltage difference was 0.278 V, the total charging time was 3065 s, the final voltage difference after setting aside for 10 min was 0.04 V, and the average voltage was 4.163 V.

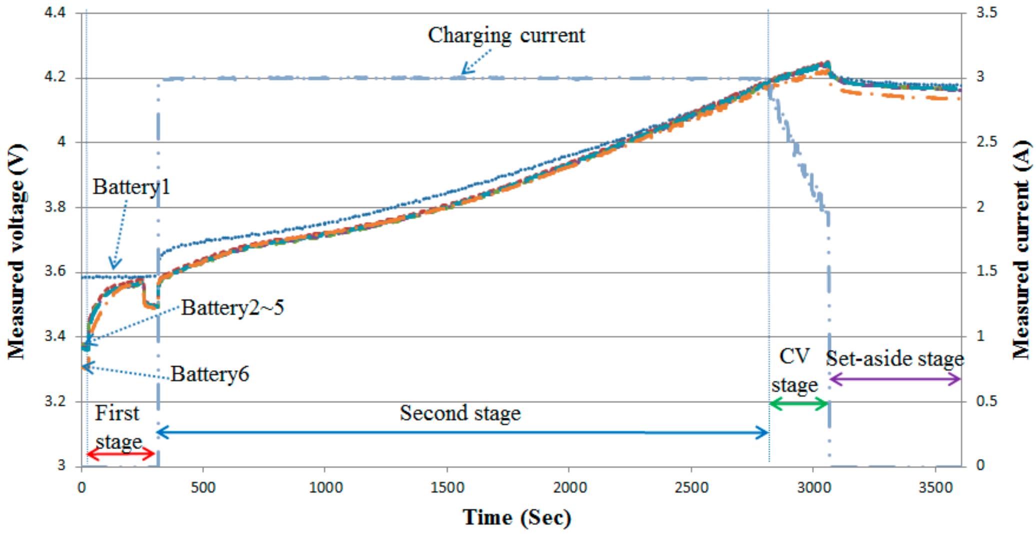

Figure 9. Shows the actual test of the first-stage balancing charge with 1 C balancing current.

Figures 10 and 11 show the actual test of the first-stage balancing charge with 0.5 C and 0.2 C balancing current; under the initial state, the maximum voltage difference, the total charging time, the final voltage difference after setting aside for 10 min, and the average voltage are shown. The balancing charges were 0.284 V, 3743 s, 0.032 V, and 4.165 V with 0.5 C. The balancing charges were 0.284 V, 5929 s, 0.028 V, and 4.161 V with 0.2 C, respectively.

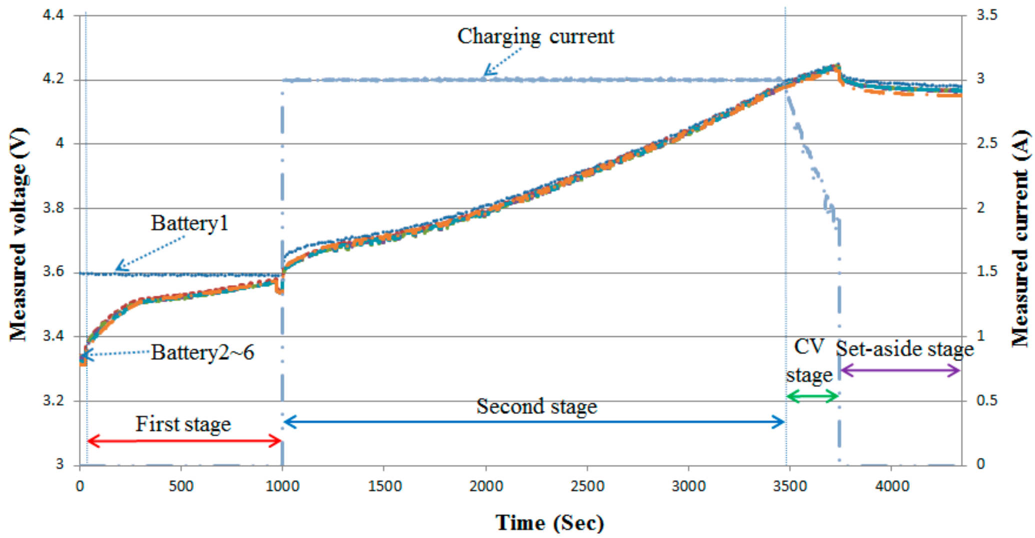

Figure 10. Shows the actual test of the first-stage balancing charge with a 0.5 C balancing current.

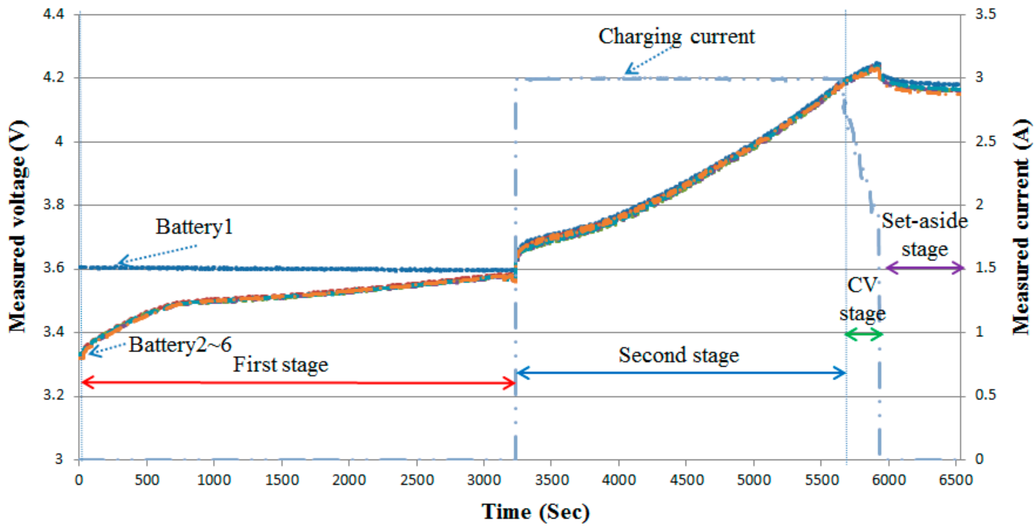

Figure 11. Shows the actual test of the first-stage balancing charge with a 0.2 C balancing current.

Table 4 shows a comparison of various charging data when different balancing currents were adopted in the first stage. This study selected 0.5 C as the first-stage balancing current.

Table 4. Comparison of the first-stage charging data with different balancing currents.

Current	Balancing Speed	Voltage Reduction after Turning off Switch	Voltage Difference after First-Stage Charging Commences
1 C	Fast	Great	Great
0.5 C	Average	Average	Average
0.2 C	Slow	Small	Small

4.2. Second-Stage Balancing Current Value Analysis

Figures 12–14 show the actual second-stage balancing charge test with 1 C, 0.5 C, and 0.2 C adopted as the balancing current; under the initial state, the maximum voltage difference, the total charging time, the final voltage difference after setting aside for 10 min, and the average voltage are shown. The balancing charges were 0.282 V, 3826 s, 0.028 V, and 4.171 V with 1 C. The balancing charges were 0.294 V, 3814 s, 0.036 V, and 4.158 V with 0.5 C. The balancing charges were 0.284 V, 3743 s, 0.032 V, and 4.165 V with 0.2 C, respectively.

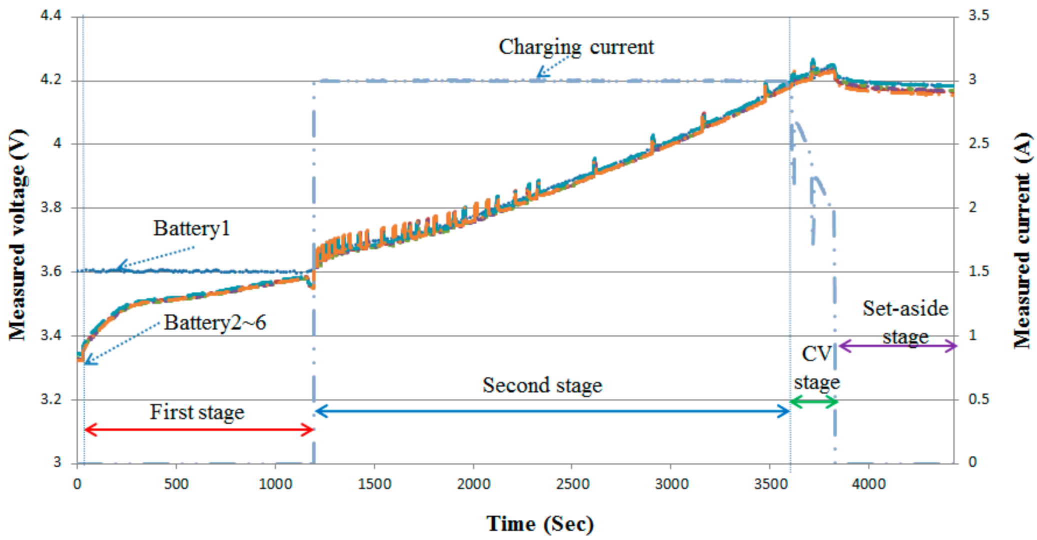

Figure 12. Shows the actual test of the second-stage balancing charge with a 1 C balancing current.

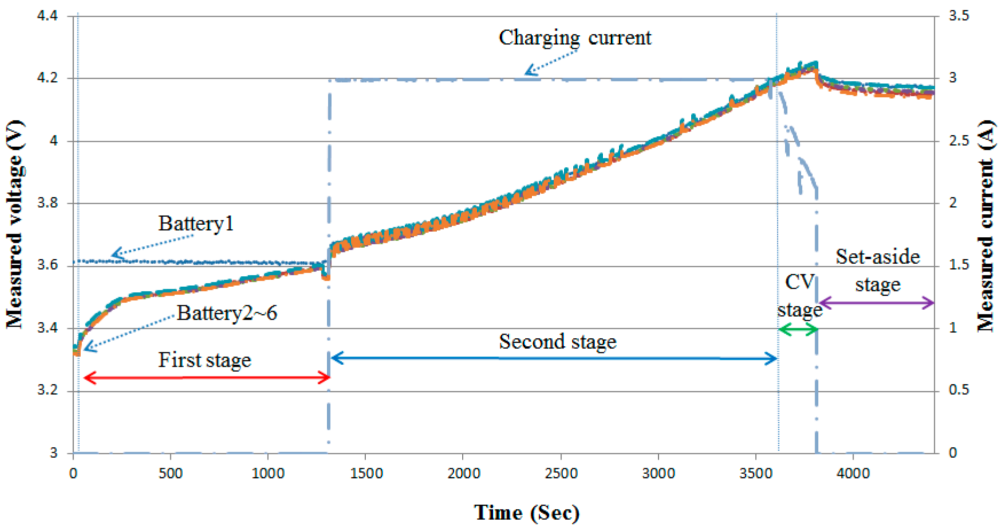

Figure 13. Shows the actual test of the second-stage balancing charge with a 0.5 C balancing current.

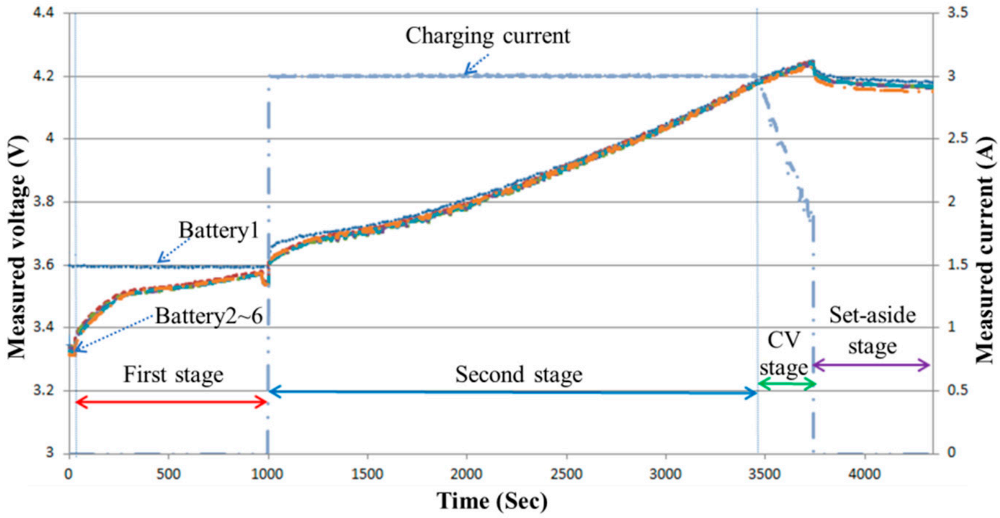

Figure 14. Shows the actual test of the second-stage balancing charge with a 0.2 C balancing current.

Table 5 shows a comparison of various charging data when different balancing currents were adopted in the second stage. The second-stage balancing current selected in this study was 0.2 C.

Table 5. Comparison of the second-stage charging data with different balancing currents.

Current	Charging Current Coupled with Balancing Charging Current	Switching Voltage Change	Voltage Stability
1 C	Great (2 C)	Great	Low
0.5 C	Average (1.5 C)	Average	Average
0.2 C	Small (1.2 C)	Small	High

4.3. CC–CV Transition Voltage Analysis

Figures 15–17 show the actual balancing charge test of CC–CV transition voltage set as 4.2 V, 4.15 V, and 4.1 V. The CV charging ties were 278 s, 418 s, and 1631 s; under the initial state, the maximum voltage difference, the total charging time, the final voltage difference after setting aside for 10 min, and the average voltages are shown. The transition voltages set as 4.2 V were 0.284 V, 3743 s, 0.032 V, and 4.165 V. The transition voltages set as 4.15 V were 0.312 V, 3,929 s, 0.036 V, and 4.172 V. The transition voltages set as 4.1 V were 0.286 V, 4,760 s, 0.024 V, and 4.218 V, respectively.

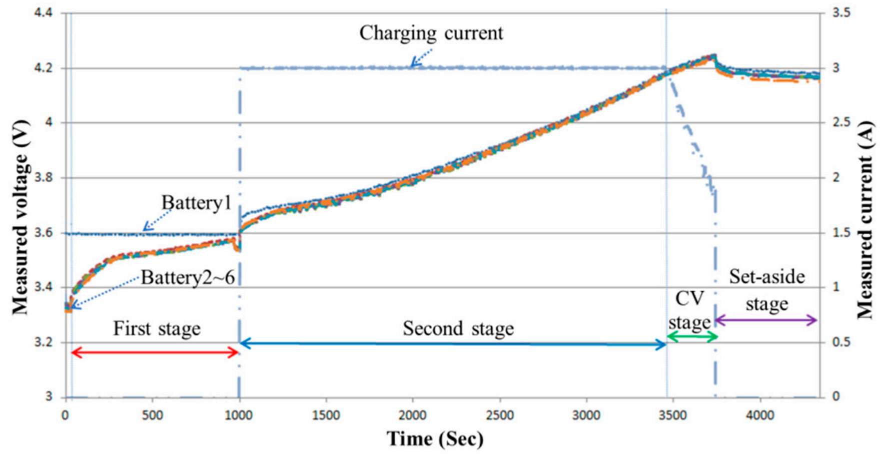

Figure 15. Shows the actual test of the balancing charging with 4.2 V set as the CC–CV transition stage voltage.

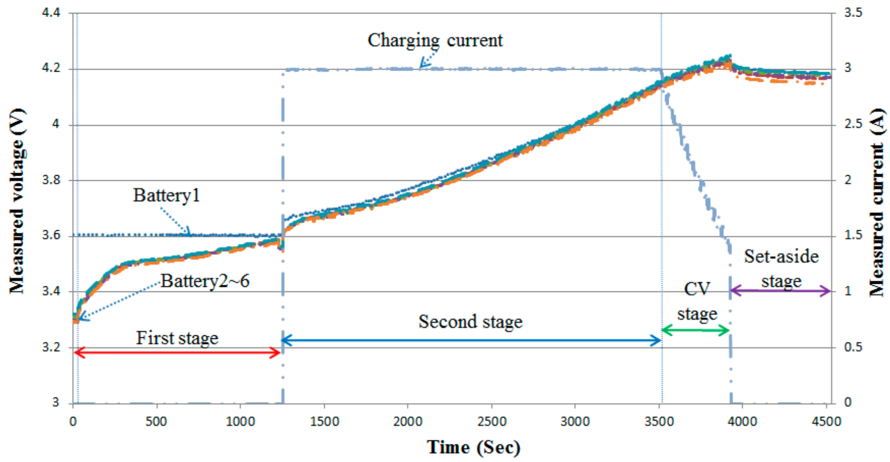

Figure 16. Shows the actual test of the balancing charging with 4.15 V set as the CC–CV transition stage voltage.

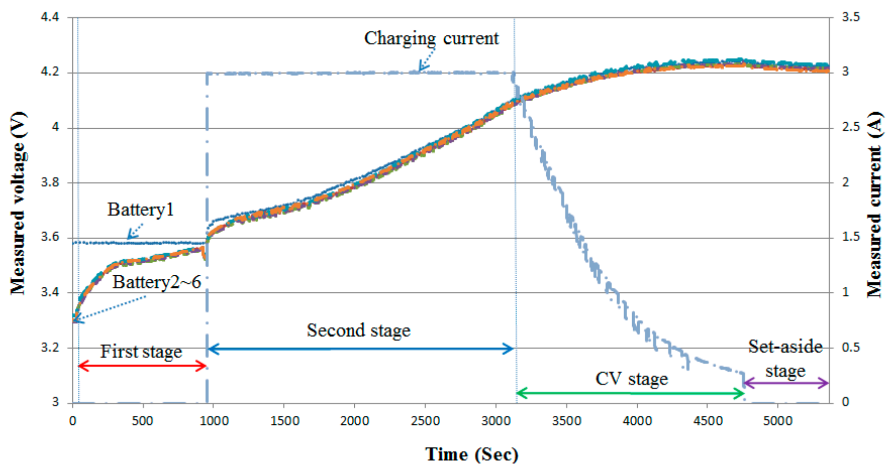

Figure 17. Shows the actual test of the balancing charging with 4.1 V set as the CC–CV transition stage voltage.

Table 6 shows a comparison of various charging data when setting different CC–CV transition voltages. The maximum CC–CV transition point of 4.2 V was selected in this study.

Table 6. Comparison of various charging data when setting different CC–CV transition voltages.

Maximum Battery Voltage	CV Charging Time	Voltage Difference after Charging Completes and Setting Aside	Average Voltage after Charging Completes and Setting Aside
4.2 V	Short (278 s)	Average (0.032 V)	Low (4.165 V)
4.15 V	Average (418 s)	Great (0.036 V)	Average (4.172 V)
4.1 V	Long (1631 s)	Small (0.024 V)	High (4.218 V)

4.4. Cut-Off Voltage Analysis

Figures 18–20 show the actual balancing charge test of 4.25 V, 4.2 V, and 4.15 V set as the voltage at the end of charging; under the initial state, the maximum voltage difference, the total charging time, the final voltage difference after setting aside for 10 min, and the average voltages are shown. The actual balancing charge test of 4.25 V were 0.284 V, 3743 s, 0.032 V, and 4.165 V. The actual balancing charge test of 4.2 V were 0.224 V, 3,313 s, 0.028 V, and 4.129 V. The actual balancing charge test of 4.15 V were 0.272 V, 3252 s, 0.022 V, and 4.044 V, respectively.

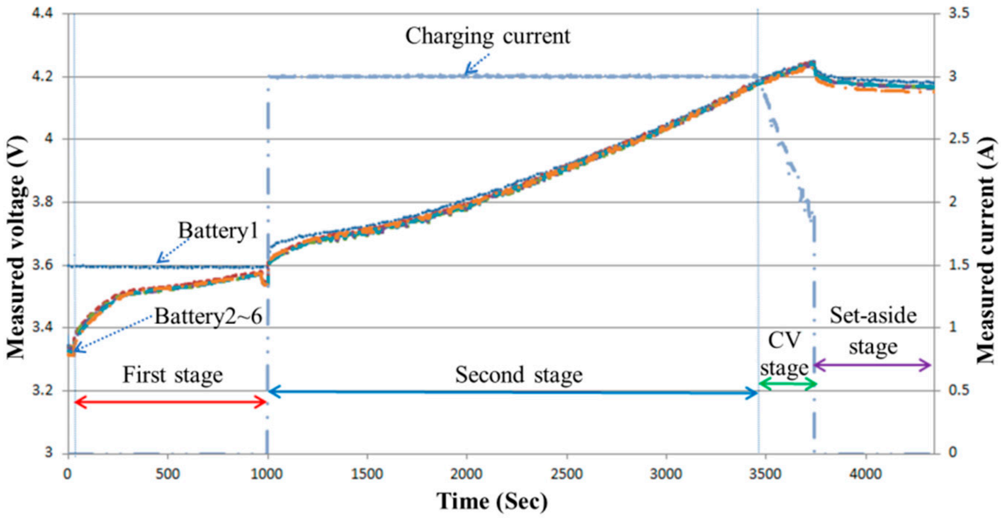

Figure 18. Actual test of the balancing charging with 4.25 V set as voltage at the end of charging.

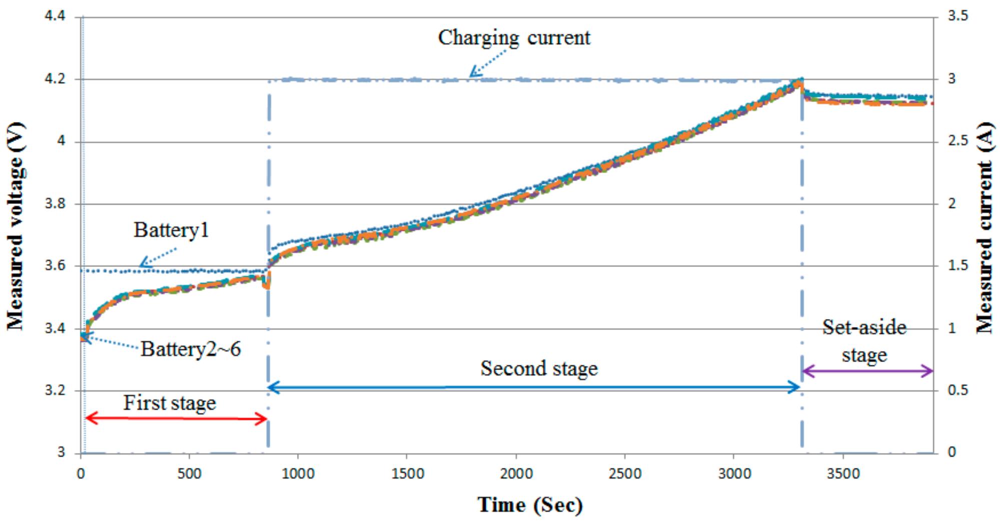

Figure 19. Actual test of the balancing charging with 4.2 V set as voltage at the end of charging.

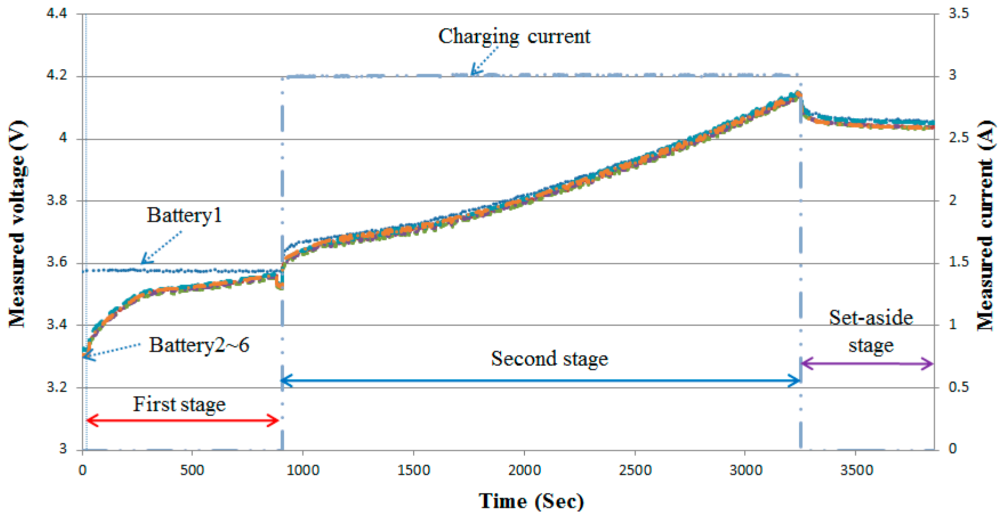

Figure 20. Actual test of the balancing charging with 4.15 V set as voltage at the end of charging.

As shown in Table 7, the comparison of various charging data when setting different voltages at the end of charging. Therefore, this paper selected 4.25 V as the end of the charging condition.

Table 7. Comparison of various charging data when setting different voltages at the end of charging.

Maximum Battery Voltage	Total Charging Time	Voltage Difference after Charging Completes and Setting Aside	Average Voltage after Charging and Setting Aside
4.25 V	Long (4357 s)	Great (0.032 V)	High (4.165 V)
4.2 V	Average (3931 s)	Average (0.028 V)	Average (4.129 V)
4.15 V	Short (3873 s)	Small (0.022 V)	Low (4.044 V)

The selected actual test conditions in this study were used to carry out six actual balancing charge tests. Using six batteries that had the maximum voltage, the actual tests were carried out to reduce the voltage difference to within 0.05 V, thereby achieving the purpose of the average voltage after the charge reaching the battery full voltage range (4.15 V–4.25 V). Figure 21 shows the actual balancing charge test result of battery 1 with the maximum initial voltage. The initial state of the battery 1 was 0.268 V, the total charging time was 3724 s, the final voltage difference after setting aside for 10 min was 0.024 V, and the average voltage was 4.161 V.

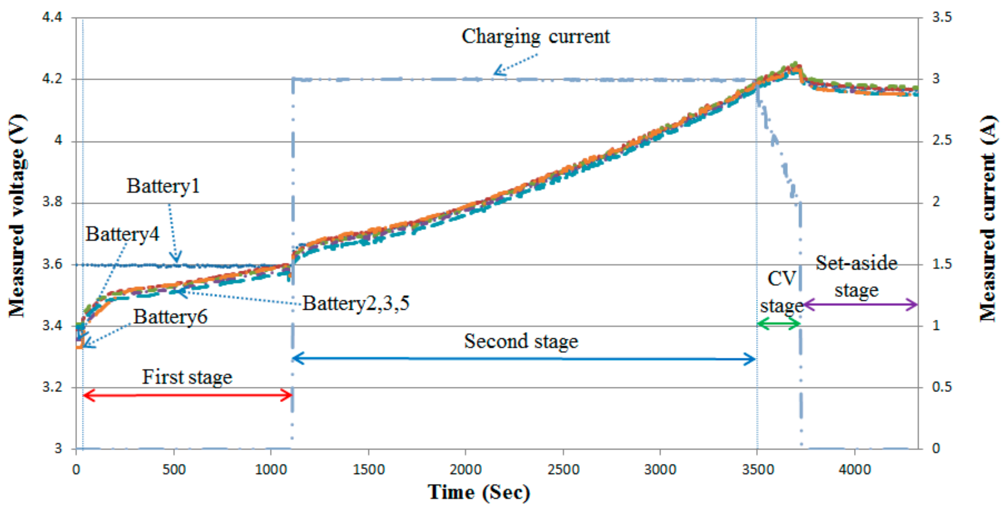

Figure 21. Actual test of the balancing charging with the greatest initial voltage.

Table 8 shows the summary table of the six batteries tests. With six batteries having the maximum voltage, the fast balancing charge was carried out on the other batteries. The average first-stage pre-balancing charging completion time was approximately 794 s, and the total average charging time was 3584 s. The six actual test results show that after completing the balancing charge, the maximum voltage difference was reduced to within 0.05 C and the battery's full voltage was achieved.

Table 8. Summary table of six actual test results.

Six Actual Test Results	With Greatest Initial Voltage					
	Battery 1	**Battery 2**	**Battery 3**	**Battery 4**	**Battery 5**	**Battery 6**
Initial voltage difference	0.268 V	0.244 V	0.274 V	0.268 V	0.244 V	0.272 V
Final voltage difference	0.024 V	0.024 V	0.05 V	0.044 V	0.032 V	0.022 V
Average voltage	4.161 V	4.163 V	4.176 V	4.179 V	4.169 V	4.171 V
First-stage pre-balancing completion time	1058 s	797 s	752 s	718 s	598 s	843 s
Total charging time	3724 s	3588 s	3494 s	3481 s	3498 s	3724 s

5. Conclusions

This study proposed a new lithium-battery pack active cell balancing circuit and a three-stage charging strategy. The charging process was divided into pre-balancing stage, a constant current main charging stage with balancing, and a constant voltage charging stage with balancing. Charging stops when the maximum battery voltage reaches the set voltage at the end of charging, which completes the entire charging process. Further, targeting the four operational conditions, namely, the first-stage pre-balancing current size, the second-stage balancing current size, the CC–CV transition voltage conditions, and the end of charging conditions, an analysis and discussion were carried out. Three conditions were selected for each item. Once the actual test had started, after a 30 s interval, the charging commenced. After charging, it was set aside for 10 min to observe the final maximum voltage difference. In this study, the six series and two parallel l battery pack was used to carry out the actual balancing charge test, which involved balancing the other batteries at the maximum voltage of six kinds of batteries, balancing the charging current, and quickly balancing the charging of other batteries. The complete data are shown in Table 8, from which the average completion time of the first stage of the balanced charging was about 794 s, and the average total charging time was about 3584 s. The test results showed that the battery cells in the battery pack were able to reduce the maximum voltage to within the 0.05 V range, under different initial maximum voltage differences, while the balancing charge time required was only 3600 s, thus, validating the feasibility of the lithium-battery pack active balancing circuit charging proposed in this study.

Author Contributions: Conceptualization, S.-L.W. and H.-C.C.; Data curation, S.-L.W. and H.-C.C.; Validation, C.-H.C.

Funding: The study was supported by Ministry of Science and Technology of Republic of China, under Grant No. MOST 108-2221-E-167-017.

Conflicts of Interest: The authors declare no conflict of interest.

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