A Series-Connected Self-Reconfigurable Multicell Battery Capable of Safe and Effective Charging/Discharging and Balancing Operations

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Abstract—**Bidirectional DC/DC converters are commonly used for charging and discharging multicell batteries under various modes, such as Pulsed Current (PC), Constant Current (CC), and Constant Current Constant Voltage (CCCV). The charge and discharge are usually terminated by the converters when battery voltages reach some threshold values. However, cell state imbalance is commonly present in traditional multicell batteries, which reduces the available capacities of the batteries in certain charge/discharge cycles and shortens the life cycles of the batteries. To solve this problem, this paper proposes a series-connected, self-reconfigurable, multicell battery with a bidirectional DC/DC converter capable of safe and effective charging, discharging, and balancing operations. The DC/DC converter uses a unified Constant Current Adaptive Voltage (CCAV) control scheme, which can fully charge each cell of the battery without damage as well as discharge the battery safely. Moreover, with the proposed design, balancing and self-healing can be achieved during operation. This enhances the reliability and energy conversion efficiency of the battery. The proposed design is validated by simulation studies for a six-cell, series-connected, lithium-ion battery pack. The proposed design is universal and can be applied to any types of batteries.**

I. Introduction

Bidirectional DC/DC converters are commonly used for charging and discharging control of multicell batteries, in which multiple cells are connected in series to provide a required voltage level. In the charge mode, the batteries can be firstly charged with a constant current lower than or equal to the rated current until the cutoff voltage is almost reached and then charged with a small current and constant voltage until they are fully charged. This is called Constant Current Constant Voltage (CCCV) charge [1], [2]. However, cell state variations are commonly present in series-connected multicell batteries [3]. Cell imbalance may cause overcharge and over-discharge of some battery cells. These unstable conditions result in a degradation of battery life and low reliability of the battery system. The problem of cell imbalance is especially severe when the battery has a long string of cells [4]. To avoid unstable conditions, commercial lithium-ion battery packs are equipped with a protection circuit. However, the protection circuit will cut off the whole battery pack when any single cell is fully charged [5], discharged, or fails, although other cells can still supply or store energy.

A commonly used method to solve the problem of cell imbalance is adding a cell balancing circuit in the DC/DC converter. Traditional cell balancing circuits use dissipative resistors, resulting in energy loss [6]. To reduce energy loss, active balancing circuits were proposed by using transformers [4], [7], capacitors [8], [9], and DC/DC converters [10], [11] with many switches. The latest products of active cell balancing integrated circuits (ICs) [12] use electronic converters to transfer charge from cell to cell during operation. However, these solutions increase the cost and volume of the battery system. Recently, several reconfigurable multicell battery topologies have been proposed for portable electronic devices [13]-[15], where highly imbalanced cells can be cut off from the batteries individually. However, these topologies only consider the discharge operation of multicell batteries and are too complex and unrealistic for the battery systems with large numbers of cells. In [16], the authors proposed a series-connected, self-reconfigurable, multicell battery design where each cell is individually controlled by two switches such that highly imbalanced cells can be cut off from the battery individually.

This paper extends the work of [16] by adding a bidirectional DC/DC converter with a unified CCAV control scheme and a balancing control scheme for series-connected, self-reconfigurable, multicell batteries. The CCAV control scheme allows the battery to be charged or discharged with a constant current or with an adaptive reference voltage, which is determined by the required voltage levels for charge and discharge, cell states, and voltage drop resulting from conduction losses of the multicell batteries. The CCAV scheme enables fast and full charge of individual cells

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without any damage. Moreover, balancing and self-healing can be achieved during charge and discharge operation, which enhances the reliability and performance of the multicell batteries. Compared to existing active balancing circuits [4]-[11] the number of balancing components, such as inductors, capacitors, and switches, in the proposed design is significantly reduced. This reduces the cost, complexity, and control effort of the total battery system. The proposed design is validated by simulation studies in MATLAB Simulink for a series-connected, six-cell, lithium-ion battery.

II. THE PROPOSED DESIGN

The proposed design consists of three parts: (1) a series-connected, self-reconfigurable, multicell battery pack, (2) a bidirectional DC/DC converter, and (3) a Battery Management System (BMS), as shown in Fig. 1.

A. Series-Connected Self-Reconfigurable Multicell Battery Pack

A series-connected, self-reconfigurable, multicell battery topology (Fig. 2) was proposed in [16]. It consists of a cell pack and a switching circuit, where each individual cell is controlled independently by only using two power switches. Compared to traditional multicell batteries using a fixed configuration, this self-reconfigurable multicell battery design is capable of self-healing from faulty cells and cells in abnormal conditions, self-balancing from cell state variations, and self-optimizing energy conversion efficiency by using cell recovery and rated current effects. These capabilities enhance the reliability and maximize the energy conversion efficiency and operating time of the battery system.

B. Bidirectional DC/DC Converter

Fig. 3 illustrates the proposed bidirectional DC/DC converter with the unified CCAV control scheme for charging and discharging control of the multicell battery. The CCAV controller outputs gate control signals G_1 and G_2 to turn on/off the two switches S1 and S2 alternatively. In the charge mode, the DC/DC converter acts as a buck converter (charger) to charge the multicell battery at the low-voltage (LV) side from a source at the high-voltage (HV) side. In the discharge mode, the DC/DC converter acts as a boost converter. The unified CCAV control scheme is used for bidirectional current flow control in the continuous conduction mode (CCM). The two switches of the DC/DC converter are complementarily controlled by a common duty generated by the unified controller [17]. The direction of the current flow I_L only depends on the relationship between the control duty cycle D and the zero current duty cycle D_o, which is equal to V_B/V_{DC}, as shown in Fig. 4. The average inductor current I_L is the same as the battery current I_B. When charging the battery, the average inductor current I_L is greater than zero. This means that the duty cycle D should be adjusted to be greater than D_o. When discharging the battery, on the other hand, the average inductor current I_L is less than zero. Consequently, the duty cycle D should be adjusted to be less than D_o.

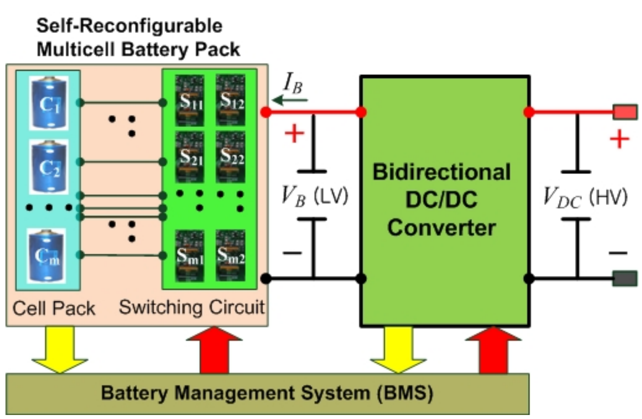


Fig. 1. The proposed self-reconfigurable multicell battery with a bidirectional DC/DC converter.

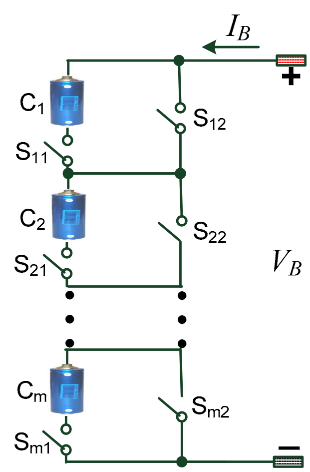


Fig. 2. The proposed series-connected, self-reconfigurable, multicell battery topology.

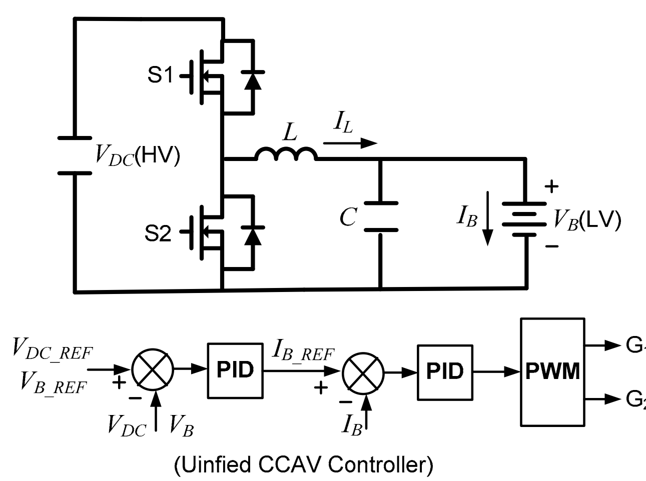


Fig. 3. The proposed bidirectional DC/DC converter with the unified CCCAV controller for charging and discharging control of the multicell battery.

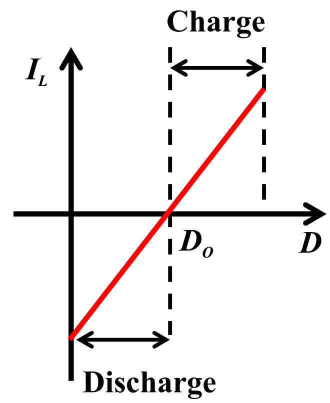


Fig. 4. Control duty cycle D versus average inductor current I_L

An output capacitor is connected at the LV side to further smooth the output current and allow the output voltage to be adjusted prior to charging the battery. In the charge mode, the multicell battery is firstly charged with a constant current (CC) until the terminal voltage reaches an adaptive reference value (V_{ref}), which is determined by the number of cells connected in the battery, charge cutoff voltage, and voltage drop caused by conduction losses of the switches. Thereafter, the voltage of each cell is kept constant; the charge current is reduced (e.g., 1/40C) as the state of charge (SOC) of each cell approaches 100%. Hence, the series-connected multicell battery can be charged fully and safely.

C. Battery Management System(BMS)

The BMS performs functions of sensing, cell modeling scheduling, gate signal generation, and interfacing with external systems for the battery, as shown in Fig. 5. The sensing and monitoring circuit monitors the voltage, current, and temperature, for each cell. The state and performance of each cell, e.g., SOC, is estimated by a model-based method using the cell voltage, current, and temperature. The optimal scheduling module determines the best configuration of cells based on the operating condition, e.g., charge, discharge, balancing, and protection, of the battery.

Fig. 6 illustrates the flow chart of the optimal scheduling algorithm, which implements the CCAV algorithm when the battery is operated in normal charge mode. In Fig. 6, I_{ABS} is the minimum charge/discharge current of the battery; SOC_{avg} is the average SOC of the battery cells; and α is a small positive number. If a battery cell is in an abnormal condition, or its SOC is lower than a low limit in the discharge mode or higher than a high limit in the charge mode, the cell will be disconnected from the battery system. The scheduling module balances the SOCs of the remaining healthy cells. First, the SOCs of the cells are sorted in a descending order. Then k (k ≤ n) cells with the lowest SOCs will be used in the charge mode. On the other hand, k cells with the highest SOCs will be used in the discharge mode. The control cycle of the optimal scheduling algorithm restarts with a certain predefined time interval or when cell conditions are changed.

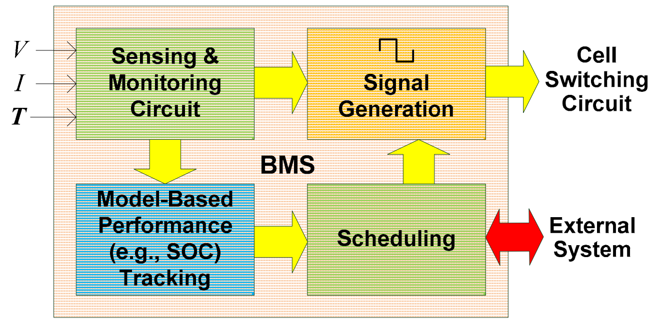


Fig. 5. The schematic of the battery management system (BMS).

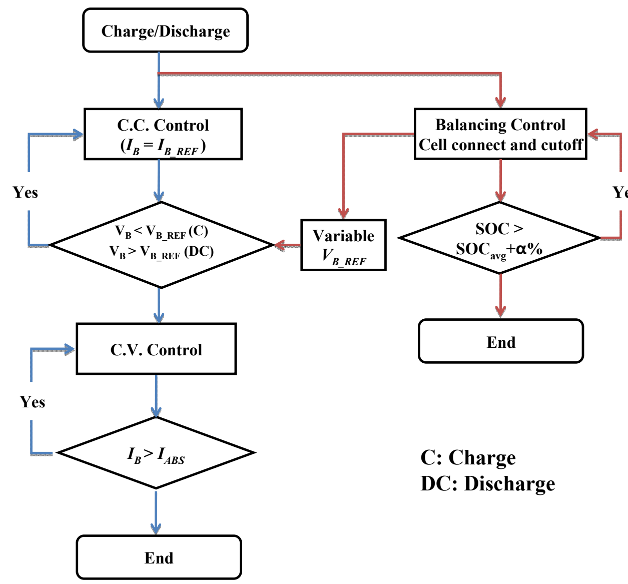


Fig. 6. The optimal scheduling algorithm.

The proposed scheduling and control scheme always tends to balance the SOCs of the battery cells. Therefore, it can fully charge and utilize the available capacity of individual cells of the multicell battery during operation.

III. Modeling of Battery Cells

An accurate battery cell model is needed to validate the proposed multicell design by simulation studies. Moreover, monitoring, control, protection, and optimization of battery systems also need an accurate battery cell model for SOC tracking, etc. In this paper, a hybrid battery model proposed in [18] is used, as shown in Fig. 7. The hybrid model enhances the electrical circuit model in [19] by replacing its left-hand-side RC circuit with a module based on the Kinetic Battery Model (KiBaM) [20] to capture the nonlinear capacity variations, such as the recovery effect and rated capacity effect, of the battery. Therefore, the hybrid battery model is capable of capturing comprehensive battery performance more accurately than the electrical circuit model by coupling the dynamic electrical circuit characteristics with nonlinear capacity effects of the battery.

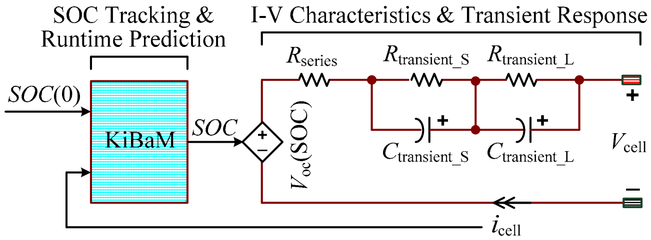


Fig. 7. The proposed hybrid battery model.

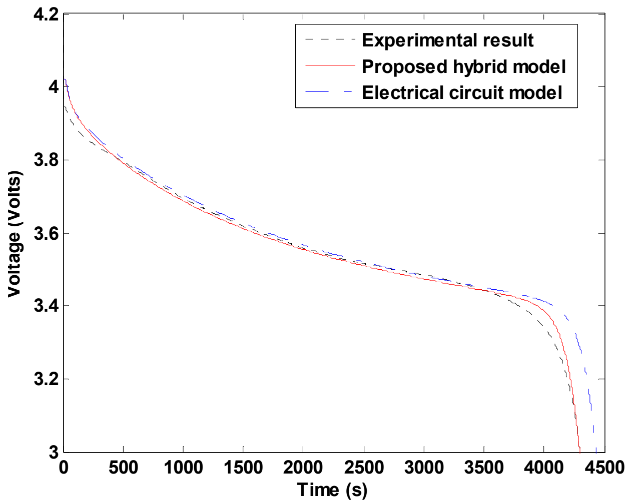


Fig. 8. Comparison of simulation results of the electrical circuit model and the hybrid model with experimental results for a single lithium-ion cell with a constant discharge current of 0.8C (2.06 A).

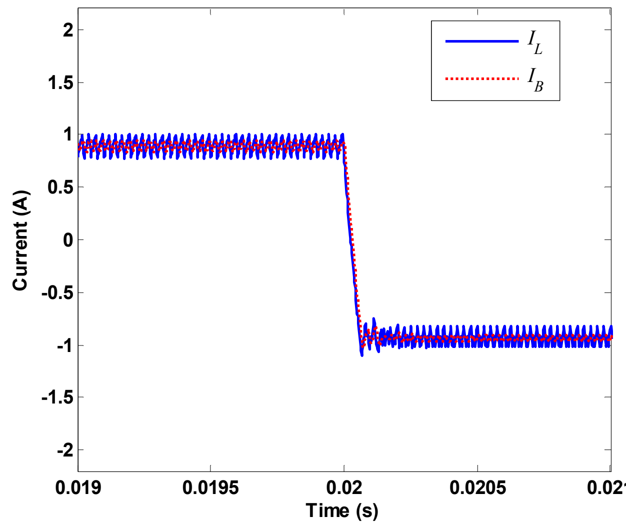
In addition, the hybrid battery model needs less computational cost than the enhanced circuit-based model in [21], thereby is feasible for real-time applications. The module on the left of the hybrid model performs the functions of SOC tracking and run time prediction for the battery. A voltage-controlled voltage source is used to bridge the SOC to the cell open-circuit voltage. The RC circuits on the right simulate the I-V characteristics and transient response of the battery.

The hybrid battery model is implemented in MATLAB Simulink. Fig. 8 compares the terminal voltage responses obtained from simulations using the electrical circuit model and the hybrid model with experimental results for a single 3.7-V, 2.6-Ah lithium-ion cell (see Appendix) under a constant discharge current of 0.8C (2.06 A). The terminal voltage response obtained from the hybrid model matches the experimental result better than that obtained from the electrical circuit model, particularly when the battery cell is close to fully discharged.

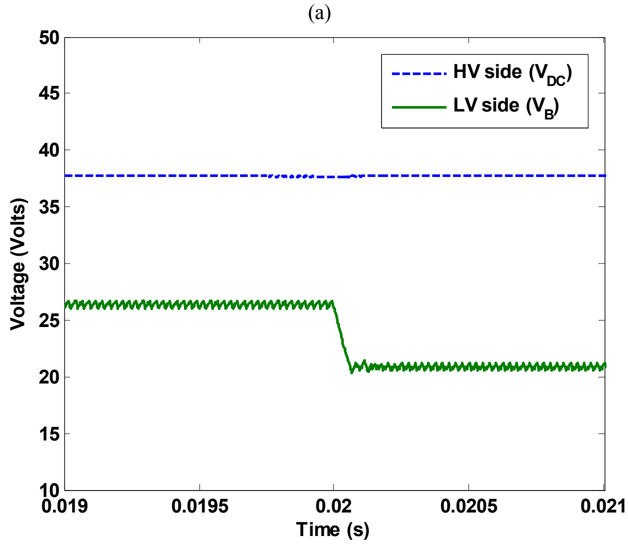
IV. Simulation Results

A six-cell, series-connected, self-reconfigurable battery pack with a bidirectional DC/DC converter is built and simulated in MATLAB Simulink. Each cell is a 3.7-V, 2.6-Ah lithium-ion cell (see Appendix), which is represented by the hybrid battery model in Section III. First, the unified controller in the bidirectional DC/DC converter is simulated to validate the bidirectional current flow control. The HV side is connected to a 40-V high capacity battery. The charging current is set to be 1 A and the discharging current is set to be –1 A. As shown in Fig. 9(a), the battery current (I_B) is stabilized at 1 A when the reference current (I_{ref}) of the controller is set at 1 A. The average inductor current (I_L) is around 1 A as well. At 20 ms, I_{B_REF} is step changed from 1 A to –1 A. Consequently, I_B changes from 1 A to –1 A quickly. During the transition the controller accurately regulates both charge and discharge currents smoothly. The battery terminal voltage also changes smoothly when the operating mode changes, as shown in Fig. 9(b).

Next, cell balancing control is tested for the proposed



(a)



(b)

Fig. 9. The current flow control between 1-A charge and -1-A discharge: (a) the inductor and battery currents; (b) the HV-side and LV-side (battery terminal) voltages.

design in charge and discharge modes. In the charge mode, assuming that the initial SOCs of Cells 3-5 are all at 35% while the initial SOCs of Cells 1, 2, and 6 are 25 %, 30%, and 40%, respectively; the value of k is predetermined to be 5 out of 6 healthy cells. In each control cycle, five cells with the lowest SOCs are selected by using the cell switching circuit and charged at 1.56 A. Fig. 10(a) shows the SOC of each cell by using the CCAV control. The SOCs of the six cells become balanced at around 3,200 s. The cells are fully charged by using the CCAV control. Fig. 10(b) shows the terminal voltages of Cells 1, 2 and 6, which all reach the charge cutoff voltage of 4.2 V at the end of the charge mode operation. Fig. 10(c) shows the terminal voltage and current of the battery pack. Under the CCAV charge control, the battery is firstly charged with a constant current; and the terminal voltage of the battery increases until it reaches the cutoff value of 21 V, since five cells are always connected in series and charged simultaneously. However, by that time the cells have not been fully charged yet. Therefore, from that moment onwards, the battery is charged with an adaptively reduced current and a constant voltage until the SOC of each cell reaches 100%.

In the discharge mode, assuming that the initial SOCs of Cells 3-5 are all at 90% while the initial SOCs of Cells 1, 2, and 6 are 85 %, 80%, and 75%, respectively. In each control cycle, five cells with the highest SOCs are selected by the cell switching circuit and discharged at 1.56 A until the SOC of each cell reaches 20%, as shown in Fig. 9(a). The SOCs of the six cells become balanced at around 2,000 s. Fig. 9(b) shows the terminal voltage of the battery pack. The discharge is terminated when the battery terminal voltage reaches the cutoff value.

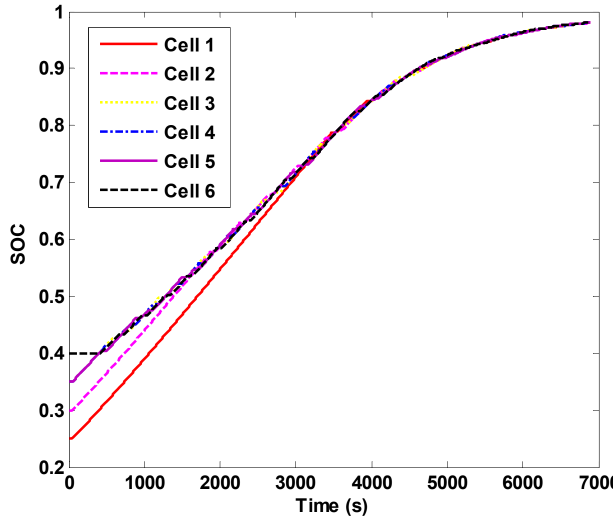
These results clearly demonstrate that the proposed series-connected, self-reconfigurable multicell battery with a bidirectional DC/DC converter is capable of safe and effective charging, discharging, and balancing operations.

V. Conclusion

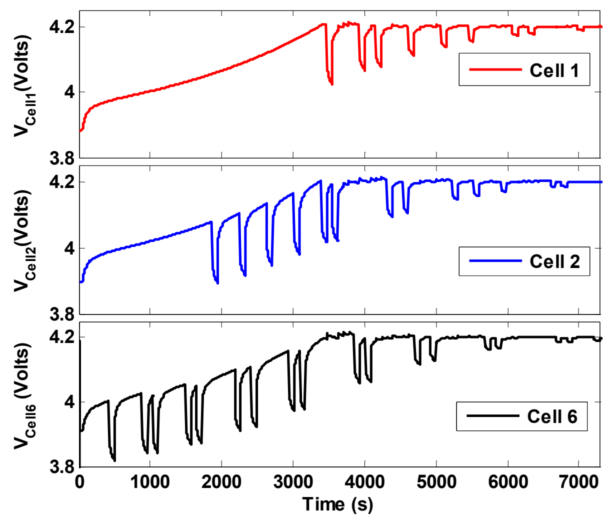
This paper has proposed a novel series-connected, self-reconfigurable, multicell battery design capable of safe and effective charging, discharging, and balancing operations. With the proposed design, individual cells of the multicell battery can be fully charged without damage. The proposed design uses a bidirectional DC/DC converter with a unified CCAV control scheme to achieve smooth and steady current flow between charge and discharge modes. Moreover, with the self-reconfigurable function, balancing control have been achieved during operation. This enhances the reliability and energy conversion efficiency and life cycle of the battery. The proposed design is universal and can be used for any types of batteries.

Appendix

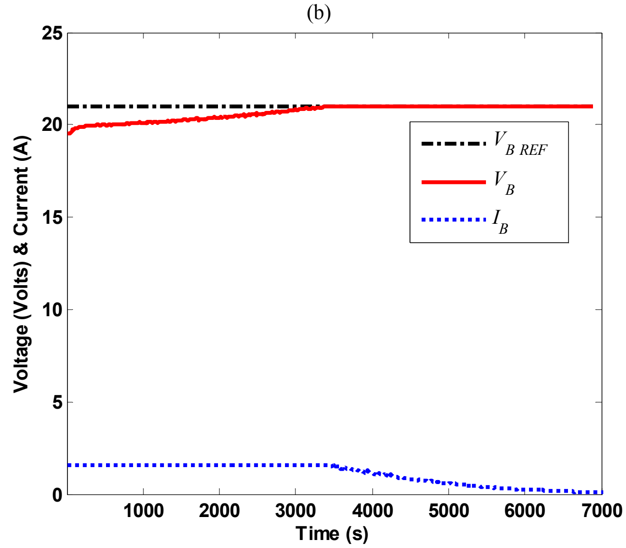
Battery cell: Tenergy 18650; nominal voltage: 3.7 V; nominal capacity: 2.6 Ah; discharge cutoff voltage (V_{cutoff}): 3 V; charge cutoff voltage (V_{over}): 4.2 V; maximum discharge current: 1C (2.6 A).



(a)



(b)



(c)

Fig. 10. Cell balancing control in the charge mode: (a) the SOC of each cell; (b) the terminal voltage of Cell 1, 2, and 6; (c) the terminal voltage and charge current of the battery.

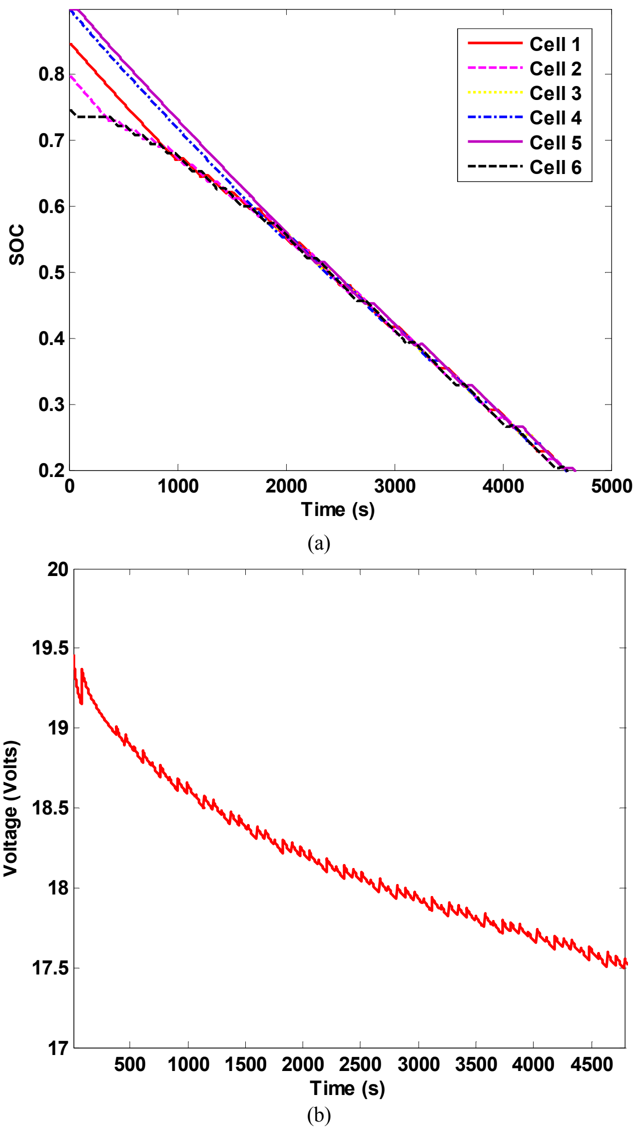


Fig. 11. Cell balancing control in the discharge mode: (a) the SOC of each cell; (b) the terminal voltage of the muticell battery.

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