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Wireless Smart Battery Management System for Electric Vehicles

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***Abstract*—This paper utilizes a Wireless Smart Battery Management System (WSBMS) to manage battery cells in Electric Vehicles (EVs). WSBMS is the cell-level Battery Management System (BMS) based on wireless communication. Compared with the conventional modularized BMS, the proposed system has the advantages of high fault tolerance and sufficient scalability. In addition, the proposed balancing algorithm based on the state-of-health (SOH) and the state-of-charge (SOC) can balance battery cells with any number, different aging states, and reasonable capacity deviation. A prototype is built, and the balancing algorithm is verified by simulation and experimental results considering four cases with different states of battery cells.**

***Index Terms*—Battery Management System (BMS), active balancing, bypass device, Electric Vehicles (EVs)**

I. INTRODUCTION

To reduce the impact of conventional fuel vehicles on environmental pollution, Electric Vehicles (EVs) have gradually come into our vision and are used in daily travel [1], [2]. Battery Management Systems (BMSs) play a critical role in EVs because it takes the responsibility to monitor the battery system and ensure the system operate in the safe condition [3]. One of the important functionality of the BMS is to balance the cells in the battery system. A simple balancing method is energy dissipation, which consumes the unbalancing energy by connecting a shunting resistor in parallel to each cell [4]. The disadvantage of this method is low efficiency due to the loss of massive energy during the balancing process so it is called passive balancing. To improve the balancing efficiency, various active balancing method were proposed, including adjacent cell-to-cell (AC2C), direct cell-to-cell (DC2C), cell-to-pack (C2P), pack-to-cell (P2C), and cell-to-pack-to-cell (C2P2C) [5], [6]. The main concept of active balancing is to transfer the unbalancing energy from the cell with higher energy to the cell with lower energy/the entire battery pack or transfer more energy to the cell with the lower energy. The disadvantages of the conventional active balancing are complex balancing circuit and control. In conventional BMSs, modularized architecture is widely applied. Several battery cells are connected in series/parallel to build a battery module that is monitored by a module sensor. Then, all module sensors are managed by a center controller [7], [8]. Low cost is a significant advantage of modularized architecture due to the only one system controller used in the BMS. However, fault tolerance is an issue. One broken cell may result in the unnormal operation of the entire battery system because all cells are connected to each other directly.

Smart Battery Management Systems (SBMSs) were proposed to improve fault tolerance. SBMSs are the cell-level BMSs that is built by numbers of smart cells. Each smart cell is an integrated module, which includes a microcontroller to measure the voltage, current, and temperature as well as estimate the state-of-charge (SOC) and the state-of-health (SOH) of the battery cell [9]. The advantages of the SBMS over the conventional modularized BMS are higher fault tolerance and high scalability due to the no direct connection among cells. There are two balancing strategies in SBMSs, which are based on the dc/dc converter and based on the bypass device, respectively. The dc/dc converters were adopted in [10], [11]. The duty cycle can be controlled to adjust the voltage of the local cell and to synchronize its SOC with other cells. For the second strategy, the balancing method is that the cell with the lowest/highest SOC is bypassed during the discharging/charging process [12]. However, this algorithm is not suitable for battery packs with large numbers of cells due to the capacity inconsistency among the cells. A similar bypass strategy was used in [13], which has the disadvantage of the wide voltage range of the battery pack.

This paper proposes a Wireless Smart Battery Management System (WSBMS) for Electric Vehicles (EVs) and proposes a balancing algorithm based on SOH/capacity and SOC to balance the battery cells with any number, different aging states, and reasonable capacity difference. Four cases of different states of battery cells are considered to verify the proposed algorithm by simulation and experimental results. Section II introduces the proposed WSBMS. Section III provides the balancing algorithm. Simulation and experimental results are presented in section IV. Conclusions are given in section V.

II. WIRELESS SMART BATTERY MANAGEMENT SYSTEM

The proposed WSBMS is the SBMS based on wireless communication, which can reduce the clutter caused by communication wires and reduce the size and weight of the system, as shown in Fig. 1. A smart cell consists of a battery cell, a bypass device, and a slave controller. The cells are not directly connected to the battery pack but through a bypass device. The slave can monitor the voltage, current, and temperature of each cell, and also estimate the SOC and SOH of the cell. At the system level, after receiving the states of all cells, the master takes the balancing decision and send the decision back to the corresponding cell. The slave controller can control the bypass device according to the received decision. Wireless communication is applied to improve the scalability of the system. The bypass device is implemented by a half-bridge circuit, which can reduce the cost due to only two switches. The operation modes of the bypass device are presented in Fig. 2. The bypass device not only plays a key role in balancing but also can bypass the bad cells to increase the fault tolerance of the system.

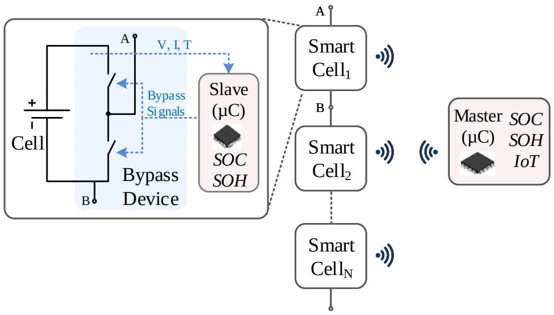
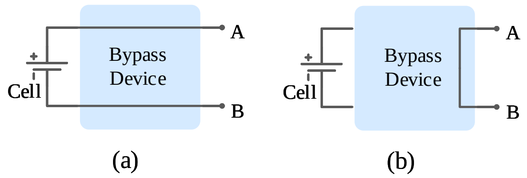


Fig. 1. Proposed Wireless Smart Battery Management System (WSBMS).



(a) (b)

Fig. 2. Operation modes of the bypass device: (a) inserted mode and (b) bypassed mode.

III. BALANCING CONTROL

The proposed balancing algorithm includes two steps. The calculation of the number of bypass cells Nb is the first step, which is important for balancing (i) large battery packs such as the ones in EVs and (ii) battery packs with a large inconsistency of capacities such as second-used battery packs that have different aging states. Nb is obtained by the total capacity deviation among cells. The second step of the algorithm is to decide which cells need to be bypassed according to the SOC of each cell. The cells are sorted in ascending order according to the value of SOCs. SOC.dev is the deviation between the maximum SOC and the minimum SOC. When SOC.dev reaches the tolerant maximum deviation, SOC.dev.tol, the bypassed cell is switched to the current cell with the lowest SOC. The detailed algorithm is presented in Fig. 3. There are many studies on SOC estimation and SOH estimation [14]–[17]. However, the estimation of SOC and SOH is not the focus of this paper, thus the SOC is obtained by the Coulomb Counting method and it assumes that the SOH is known.

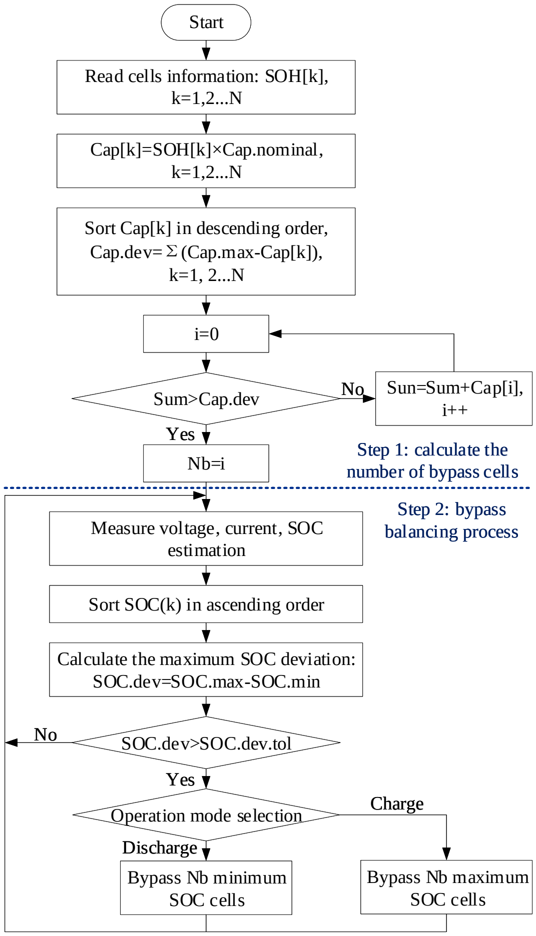


Fig. 3. Proposed balancing algorithm.

IV. SIMULATION AND EXPERIMENTAL RESULTS

In the following, four different cases are considered to verify the proposed balancing algorithm. Case 1 and Case 2 present the balancing of the battery cells with the same nominal capacity and aging states. Case 3 shows the balancing results of the battery cells with different aging states. Case 4 provides the balancing results of the battery cells with different nominal capacities.

A. Simulation Results

The simulation results with 24 battery cells are provided for the theoretical verification of a large battery pack. The RC model is built by the laboratory data obtained from a 60Ah/3.2V LiFePO4 cell. The key parameters of the simulation are presented in Table II. The Worldwide Harmonised Light Vehicle Test Procedure (WLTP) profiles are used for the verification in PLECS. Fig. 4-Fig. 7 are the balancing results for case 1, case 2, case 3, and case 4, respectively. The simulation results show that battery cells are being kept balanced for four cases, which are corresponding the four cases of experimental results.

TABLE I
KEY PARAMETERS IN SIMULATION

Simulation parameters	**Case 1**	**Case 2**	**Case 3**	**Case 4**	
Number of battery cells	24	24	24	20	4
Nominal capacity [Ah]	60	60	60	60	40
Initial variation in capacity [%]	5	5	20	5	
Initial variation in SOC [%]	1	5	1	1	
Figure of simulation results	Fig. 4	Fig. 5	Fig. 6	Fig. 7	
Number of bypassed cells for unbalancing results	0	0	1	1	
Number of bypassed cells for balancing results	1	1	3	2	

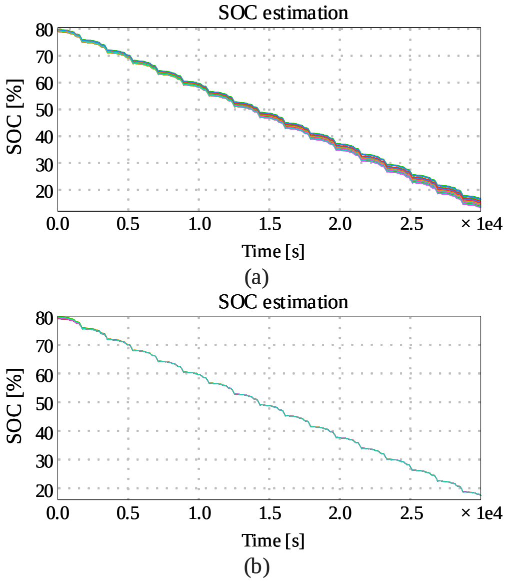


Fig. 4. Simulation results for Case 1: (a) unbalancing results and (b) balancing results.

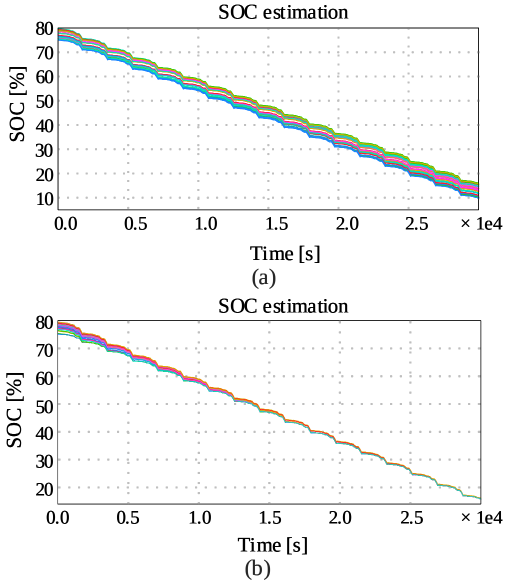


Fig. 5. Simulation results for Case 2: (a) unbalancing results and (b) balancing results.

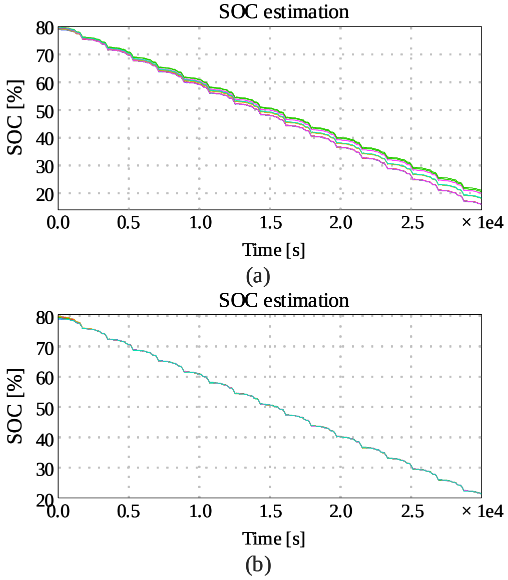


Fig. 6. Simulation results for Case 3: (a) balancing results without Step 1 and (b) balancing results with the proposed algorithm.

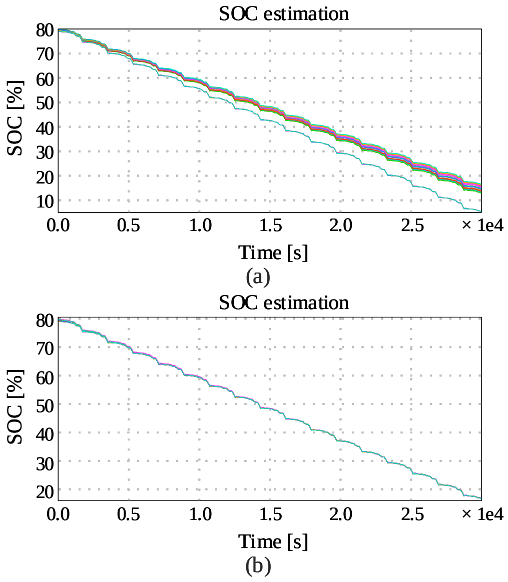


Fig. 7. Simulation results for Case 4: (a) balancing results without Step 1 and (b) balancing results with the proposed algorithm.

B. Experimental Results

A prototype of the proposed WSBMS is presented in Fig. 8. The slave controller CC3220MOD can communicate with the master controller, a Krtkl Snickerdoodle board driven by Zynq® processor 7020 with a WiLinkTM 8 module, via the Wi-Fi feedback [18]. The simulation results have verified the proposed algorithm can balance the battery pack with large numbers of battery cells. Here, four battery cells are implemented in the Battery Cell Simulators.

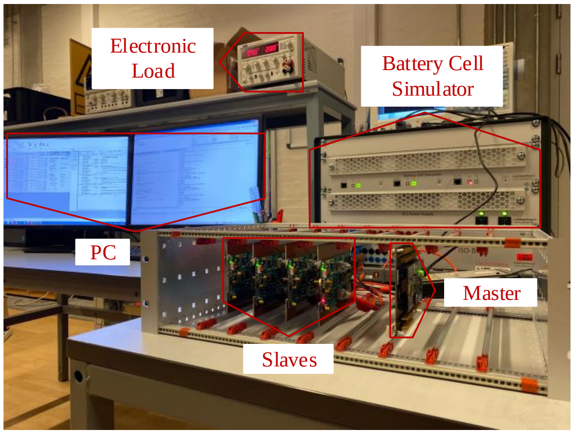


Fig. 8. Prototype of the proposed Wireless Smart Battery Management System (WSBMS).

Case 1: For a battery pack with the same initial SOC, there is still a slight difference among the cell's capacities. In Fig. 9(a), the imbalance is gradually increasing during the discharging process. The battery pack can achieve a balanced operation by using the bypass strategy, as shown in Fig. 9(b).

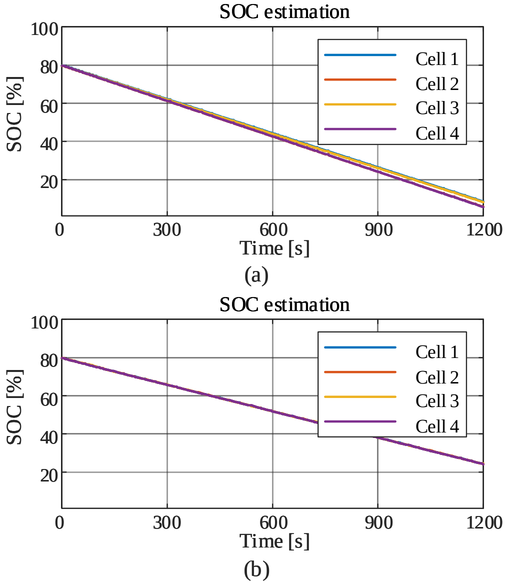


Fig. 9. Experimental results for Case 1: (a) unbalancing results and (b) balancing results.

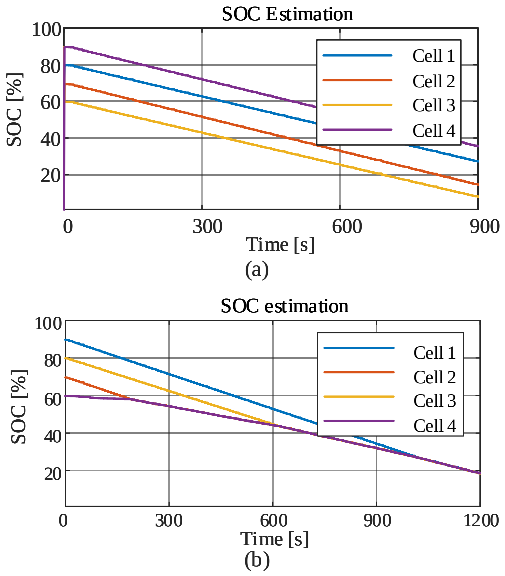


Fig. 10. Experimental results for Case 2: (a) unbalancing results and (b) balancing results.

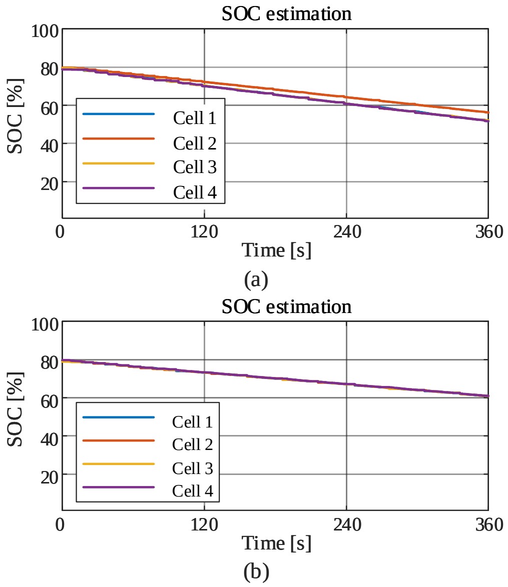


Fig. 11. Experimental results for Case 3: (a) balancing results without Step 1 and (b) balancing results with the proposed algorithm.

Case 2: Four cells with a 10% SOC difference are tested during the discharging process. Fig. 10(a) shows the results without balancing control. The balancing result using the proposed algorithm is presented in Fig. 10(b). Due to a large difference in the initial SOCs, it needs more time to reach the balancing state compared with other cases.

Case 3: This is the test of battery cells with a maximum of 40% different aging state. The SOC declining rate of the cell with a slightly aging state (Cell 2) is slower than that of the other three severely aging cells, which results in unbalancing during the discharging process, as shown in Fig. 11(a). Thus,

TABLE II
KEY PARAMETERS IN EXPERIMENT

Experiment parameters	Case 1	Case 2	Case 3	Case 4	
Number of battery cells	4	4	4	2	2
Nominal capacity [Ah]	1	1	1	1	2.2
Cell capacity [Ah]	[1.01 1.00 0.99 0.98]	[1.01 1.00 0.99 0.98]	[0.50 0.55 0.60 0.90]	[1.00 1.01 2.20 2.19]	
Initial variation in SOC [%]	[80 80 80 79]	[60 70 80 90]	[80 80 80 79]	[80 80 80 79]	
Figure of experimental results	Fig. 9	Fig. 10	Fig. 11	Fig. 12	
Number of bypassed cells for unbalancing results	0	0	1	1	
Number of bypassed cells for balancing results	1	1	2	2	

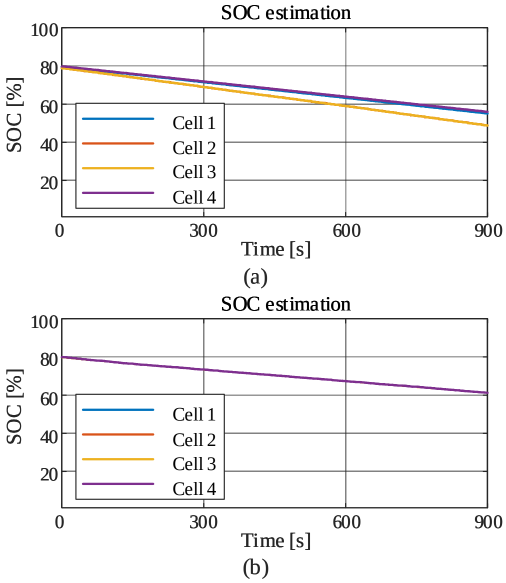


Fig. 12. Experimental results for Case 4: (a) balancing results without Step 1 and (b) balancing results with the proposed algorithm.

it is necessary to calculate the number of bypass cells. Fig. 11(b) shows the balancing results with the proposed control algorithm.

Case 4: Two 1 Ah cells and two 2.2 Ah cells are tested in this case. In Fig. 12(a), batteries with smaller capacities have faster discharge rates, so it is difficult to achieve balance when only one cell is bypassed. By adopting the proposed algorithm, the battery pack is kept balancing state throughout the whole process, as shown in Fig. 12(b).

C. Discussion

The maximum SOC deviations for four cases during the discharging process are presented in Fig. 13. The blue curves are the maximum SOC among four cells of the unbalancing conditions. The maximum SOC deviation of the unbalancing condition is related to the initial SOC of four cells: the larger the difference among the initial SOC or SOH/capacity of cells, the larger the SOC deviation at the end of the discharging process. The red curves are the maximum SOC among four cells of the balancing conditions, which can control the maximum SOC deviation within 1% even in the extreme condition.

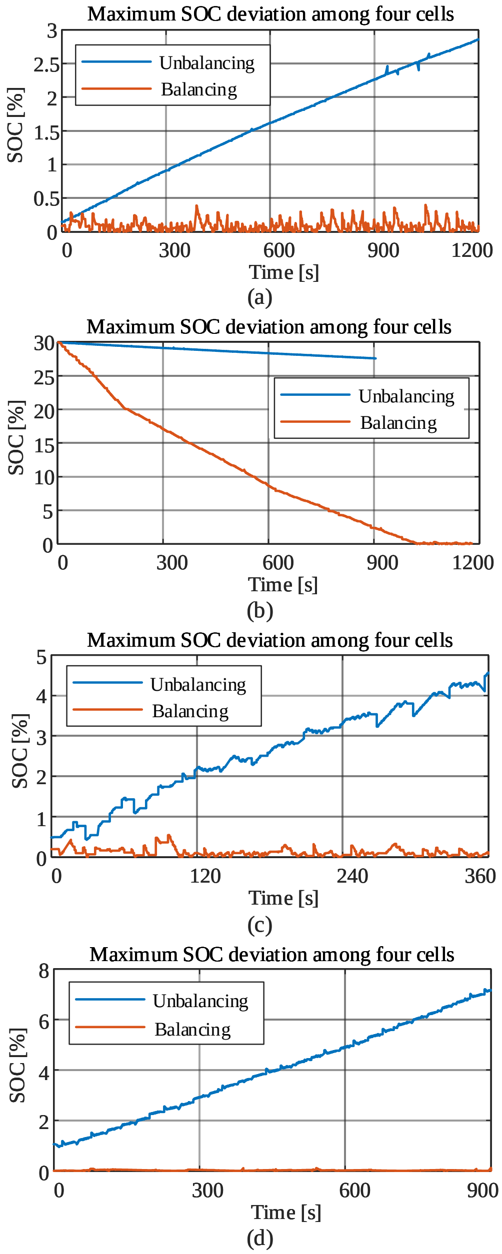


Fig. 13. Maximum SOC deviation among four cells of the unbalancing results and the balancing results: (a) Case 1, (b) Case 2, (c) Case 3, and (d) Case 4.

For example, in Case 2 and Case 4 that represent the large initial deviation of SOC and the large difference in capacities respectively, the SOC of four cells can gradually reach the equalization during the discharging processes.

There are two issues that need to be noticed. The first one is that there were some moments all four cells were inserted during the discharging process. Take the balancing process of Case 2 as an example, Cell 4 should be bypassed at the beginning due to the lowest SOC. However, the SOC of Cell 4 has a slightly declined trend at the beginning of the discharging process, as shown in Fig. 10(b). This is because the master controller requests the SOC data of each cell from the slave controller every once in a while, but sometimes the communication might be temporarily lost or lagging. When this situation happens, the slave controller will execute the safe mode, which makes all cells inserted into the circuit to ensure that the power can be delivered normally. Therefore, all cells will be discharged, and the SOC will decrease. However, this will not affect the equalization throughout the discharge process because the master controller and slave controller re-establish the connection soon. The second matter is that the pack voltage has a drop due to the bypassed cells, but this will not be a problem in the battery pack in EVs. The battery storage system of EVs includes about 100 cell modules connected in series. Moreover, a dc/dc converter will be the output of the battery pack to ensure a stable dc voltage. Thus, a slight voltage drop caused by the bypassed cell can be ignored.

V. CONCLUSIONS

In this paper, a WSBMS is used to manage battery cells for EVs. The proposed system has the advantages of high fault tolerance and sufficient scalability compared with the traditional modularized BMS. All information is exchanged in the system via Wi-Fi communication, which avoids cluttered wires. A two-step balancing algorithm is proposed to equalize the cells with different states, including SOC, SOH, and capacity. To demonstrate the advantage of the proposed algorithm, four cases that present different states of battery packs are considered. The simulation and experimental results verified that the proposed algorithm can balance the battery cells with any number, different aging states, and reasonable capacity deviation.

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