A highly-integrated and efficient commercial distributed EV battery balancing system

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Abstract: This paper focuses on the imbalance problem of serial cells in lithium-ion batteries applied in electric vehicles (EVs). In order to meet more strict requirements of size, efficiency, cost, and reliability in commercial application, a highly-integrated and efficient distributed battery balancing system is developed. In the system, each balancing node (BN) and its controller, a designed specific integrated circuit (IC), are independent, distributed and integrated in an IC-packaged module. Besides, a 50% state-of-charge (SOC)-aligned balancing strategy is proposed and applied. The experiment and commercial application results show the designed balancing system performs excellently in improving battery capacity and extending cycle life.

Keywords: battery balancing system, commercial, EV, highly-integrated, specific IC

Classification: Power devices and circuits

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1 Introduction

In electrical vehicle (EV) application, a battery pack is normally composed of many battery cells (BCs) connected in series or parallels to meet the voltage, power and capacity needs [1]. However, due to variations in internal characteristics and differences in operating conditions, batteries may suffer from imbalance problems.

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mainly imbalance of remaining effective capacity and state-of-charge (SOC) [2, 3]. Imbalance will reduce the total effective capacity of battery pack and shorten charge-discharge cycle life. With rapid development of EV, battery cell balancing has attracted much attention. Researches on battery balancing mainly include balancing methods [4, 5, 6, 7, 8], strategies [9, 10, 11, 12] and control algorithms [13, 14, 15, 16]. Related reviews can be found in [17, 18, 19].

Previous battery balancing systems normally implement discrete devices to constitute balancing nodes (BNs). The control of BNs, including switch driving, measuring, communication and so on, are handled by DSPs or microchips. Therefore the systems suffer problems in design complexity, size, cost, efficiency and reliability, and hence may fail to meet strict requirements for commercial application.

In order to handle these problems, a highly-integrated and efficient distributed active balancing system is developed. Bidirectional Buck-Boost converter is implemented in the balancing node (BN), and a specific IC is designed to control the BN for better efficiency and lower cost. Each individual BN and its controller are independent and distributed, which makes the design modular, simple and flexible. The BN and control IC are integrated in an IC-packaged module for better reliability and smaller size. The system applies a novel 50%SOC-aligned balancing strategy to achieve good performance in both improving battery capacity and prolonging cycle life. The designed balancing systems have been successfully applied to 3000 commercial battery packs and served on 750 EVs since 2013.

2 Battery balancing strategy
2.1 Battery imbalance description

As Fig. 1(b) shows, at the very beginning, the battery cells are healthy and well balanced. However, capacity loss and imbalance will gradually appear due to the aging, internal differences (like self-discharge differences) and external differences (like temperature) as shown in Fig. 1(c). The imbalance will reduce the total effective capacity of the battery pack and aggravate the aging and differentiation.

![Battery cell status description](image-url)
2.2 Battery balancing strategy

A 50%SOC-aligned balancing strategy is proposed and applied in the balancing system. Fig. 2 shows the demonstration of the proposed balancing strategy.

Unlike the SOC-synchronized strategy, the 50%SOC-aligned strategy does not need to equalize the SOCs all the time. The SOC of each cell may be different in a charge-discharge cycle. But they are balanced to ensure they are charged and discharged equally, and the SOCs are symmetrical about 50%. It can be observed in Fig. 2 that, after 50%SOC-aligned, the total equivalent SOC of battery pack $SOC_{tot}$ is consistent with the weakest battery cell (Namely $SOC_1$). Other battery cell SOCs are not consistent with the $SOC_{tot}$, but approximately conform to the mapping relationships as Fig. 3 shows.

Assume the operation range of $SOC_{tot}$ in a charge-discharge cycle as $[SOC_{tot_{min}}, SOC_{tot_{max}}]$, and the operation range of $SOC_k$ as $[SOC_{k_{min}}, SOC_{k_{max}}]$. Define the mapped $SOC_k$ by the 50%SOC-aligned standard as $\hat{SOC}_k$, then the $\hat{SOC}_k$ can be calculated as Eq. (1). Consequently, all the battery cells are balanced by 50%SOC-aligned standard if only the mapped $\hat{SOC}_k$ are equalized.

$$\hat{SOC}_k = 0.5 + (SOC_k - 0.5) \cdot \frac{SOC_{k_{max}} - SOC_{k_{min}}}{SOC_{tot_{max}} - SOC_{tot_{min}}}$$

(1)

Compared with SOC-synchronized balancing strategy, the 50%SOC-aligned strategy is likely to provide less total effective capacity. However, 50%SOC-aligned strategy has merits as follows:

1) Higher efficiency. Balancing execution (energy transfer) consumes power. With 50%SOC-aligned strategy, little balancing execution is needed once the battery
cells have been balanced. Whereas, with SOC-synchronized strategy, the balancing execution is always needed to synchronize SOCs of battery cells with different capacities.

2) Better anti-varying and anti-aging. Battery cells with different capacities are charged and discharged by the same quantity, which means the cells with less capacity do not need to go through more changing and discharging in a cycle. This avoids speeding up aging of the weak cells.

With these considerations, the 50%SOC-aligned balancing strategy is applied in the balancing system.

3 Battery balancing system

3.1 Balancing circuits

With good flexibility and modularization capability, Buck-Boost bidirectional converter is selected as the balancing circuit topology. As shown in Fig. 4(a), Buck-Boost works as balancing node (BN), connecting two battery cells, and transferring energy between them. The transferring direction, current and transferred energy are all controlled by switches S1 and S2. For example, when S2 is off and S1 operates, the energy is transferred from BC #n to BC #n+1.

Balancing nodes can be combined to constitute a multilevel distributed balancing structure to balance more number of connected battery cells. Fig. 4(b) shows the example of eight battery cells. The basic rule is that, the higher level BNs are in charge of the adjacent lower level BNs. In this way, the energy can be transferred between any battery cells.

This multi-level structure can be extended to any number of connected battery cells, as shown in Fig. 5. Normally, for a battery pack consisting of K battery cells, K-1 balancing nodes are needed.

3.2 Battery balancing control

The whole battery balancing control can be divided into system-level control and node-level control. System-level control is supposed to make the energy transfer
plan and give commands to node-level control. Then node-level control accomplish the energy transfer by controlling switches according to the given commands.

Fig. 6(a) gives the system-level control flow chart. The measured external parameters $Y_i$ includes terminal voltages, temperatures, and currents of each battery cells. Then the battery cell SOC $SO_{C_k}$ and battery pack SOC $SO_{C_{tot}}$ are estimated by Extended Kalman Filter (EKF) algorithm [20], in which a three RC pairs equivalent circuit cell model with mean hysteretic polarization is used. The balancing current is taken account in the control model of the state equation while the voltage ripples are treated as additive measurement noise. $SO_{C_k}$ is calculated according to Eq. (1). The $R_{SOC}$ is the range of $SO_{C_k}$, $T_{SOC}$ is a preset threshold of $R_{SOC}$.

After turn-on, the battery system will go through self-check firstly. Then, it measures external parameters $Y_i$ and estimates $SO_{C_k}$, $SO_{C_{tot}}$ and $SO_{C_k}$. If $R_{SOC}$ is over $T_{SOC}$, the system will make the energy transfer plan and give corresponding commands to all the node-level controllers. After all the balancing nodes finish the
task, the system will check the battery balance state again and decide whether to transfer energy again or not, until the battery is balanced as expected.

Fig. 6(b) shows the node-level control flow chart. Node-level control begins after the balancing node receives commands from system-level control. It measures external parameters (redundant-purposed) and checks the main circuits and the balance status (redundant-purposed). Then according to the balancing commands and current situation, it determines internal control parameters and generates PWM signals. The battery states are fed back all the time, so that the node-level control can adjust control parameters and ensure the balance task is accomplished.

A simple example is given in Fig. 7 to demonstrate the energy transfer process. Currently, the mapped $SOC$ of these four BCs are 47%, 40%, 43% and 50% respectively. The average $SOC$ is 45%. In order to balance all $SOC$ to 45%, BC#1 should reduce $SOC$ by 2%, BC#2 should increase $SOC$ by 5%, BC#3 should increase $SOC$ by 2%, and BC#3 should reduce $SOC$ by 5%. Therefore BN#1 needs to transfer 2% $SOC$ from BC#1 to BC#2. BN#2 needs to transfer 2% $SOC$ from BC#4 from BC#3. BN#3 should transfer 3% $SOC$ from BN#2 (BC#3+BC#4) to BN#1 (BC#1+BC#2).

**3.3 Battery balancing system structure**

Fig. 8 shows the structure of battery balancing system with application-specific ICs. The system-level controller needs to handle a lot of calculation and communication, therefore the central controller can be served by DSP or microchip. Balancing node controller takes charge of the node-level control. Considering the burdensome task and large number, application-specific ICs are designed to serve balancing node controllers for better balancing efficiency and lower cost.

The balancing system is designed for EV batteries, so for better reliability, miniaturization, efficiency and modularization, the balancing node controller, balancing node circuits, measuring and protection are all integrated in an IC-packaged module, as shown in Fig. 8. It can be seen that the designed control IC and IC-packaged module are of small size.
4 Experiment and commercial application results

The battery balancing systems have been applied to 3000 battery packs and served for 750 EVs since 2013 in Hangzhou, China. The EV battery pack is consist of 24 battery cells. The battery pack is designed to have output voltage of 80 V and capacity of 60 Ah. Fig. 9 shows the photos of a battery pack and the battery assembling site. The size of the battery pack is 726 mm × 220 mm × 283 mm (length × width × height). The battery balancing board height is required to be within 12 mm.

In order to verify the effectiveness of the designed balancing system, experiments are carried out on battery packs with imbalance. The imbalanced battery cells have capacities ranging from 62 Ah to 66 Ah and SOCs from 45% to 90%. As shown in Fig. 10, before the balancing system is turned on, the total effective capacity of the battery pack is only about 28 Ah. Whereas, about 8 charge-discharge cycles after the balancing system is turned on, the total effective capacity goes up to 62 Ah. Fig. 11 shows the voltage characteristics of the battery cells before and after being balanced by designed balancing system. It can be observed that, the...
battery cells show nearly uniform characteristics in a cycle of charging and discharging after being balanced. These results show the designed system is capable of balancing the battery well and improving battery capacity quickly.

![Fig. 10](image1.png)

**Fig. 10.** Experimental result of the total effective capacity improved by designed balancing system.

![Fig. 11](image2.png)

**Fig. 11.** The voltage characteristics of the battery cells before and after being balanced by designed balancing system. (a) Imbalanced. (b) Balanced.

More than 2500 charge-discharge cycles are carried out to test anti-aging performance of the designed balancing system. The result is given in Fig. 12. It shows the cycle life is extended from about 1000 to 2000 with the help of designed balancing system (EV battery cycle life end is normally defined by 20% capacity loss). Cars with new fully charged batteries can run about 80 km. Table I shows that, after about 230 charge-discharge cycles, batteries with designed balancing system still keep mileage of over 76 km, whereas the battery without designed balancing system only has mileage of 57 km. These results prove the designed balancing system shows good performance in extending cycle life.

In conclusion, these experiment and commercial application results prove this designed balancing system is effective in improving battery capacity and extending cycle life.
5 Conclusion

This paper presents a highly-integrated and efficient commercial distributed battery active balancing system with application-specific ICs. The balancing strategy, balancing node circuits, control, and system structure are introduced. The designed balancing systems have been applied successfully in 3000 commercial battery packs and served on 750 EVs since 2013. The experiment and commercial application results show the designed balancing system performs excellently in improving battery capacity and extending cycle life.

Table I. Commercial application results

| Batteries                     | Distance per charge | Charge-discharge cycles |
|-------------------------------|---------------------|-------------------------|
| New                           | 80 km               | 0                       |
| #1 with proposed strategy     | 78 km               | 235                     |
| #2 with proposed strategy     | 79 km               | 245                     |
| #3 with proposed strategy     | 76 km               | 232                     |
| #4 without proposed strategy  | 57 km               | 237                     |

Fig. 12. Charge-discharge cycle life test results.