A Novel Switched Capacitor Circuit for Battery Cell Balancing Speed Improvement

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***Abstract*—To improve battery cell balancing speed, a novel switched capacitor (SC) circuit combining the conventional SC circuit and the optimized SC circuit is proposed in this paper. It has the advantage that the balancing speed is independent of number increase as well as initial voltage variation of battery cells. The equivalent model of the proposed circuit is developed and analyzed in this paper. Compared with the optimized SC circuit, the balancing speed of the proposed circuit is doubled. Simulation comparisons with the conventional SC circuit and the optimized SC circuit under different numbers and initial voltages of battery cells are carried out in PSIM environment. Simulation results show 82% and 50% decrement in the balancing time averagely compared with the conventional SC circuit and the optimized SC circuit, respectively.**

***Index Terms*—Cell balancing, capacitor based circuits, equivalent model, PSIM.**

I. Introduction

Due to the high power and energy density, lithium-ion batteries are widely used in various applications such as electric vehicles (EVs) and renewable energy storage systems [1]. In most applications, the battery pack consists of hundreds of lithium-ion battery cells in order to meet high voltage and high power demands [2]. However, owing to manufacturing inconsistencies, environmental variances, capacity degradation with aging, and difference in self-discharge rates, there is imbalance between battery cell voltages or state of charge (SOCs) [3]. Furthermore, as the batteries are charged and discharged with time, the voltage or SOC imbalance tends to become more and more severe. As a result, the available capacity and lifecycle of the battery pack are reduced and safety hazards such as fire or explosion may even happen because of the overcharge of battery cells [4]. Consequently, the battery management system (BMS) is essential to protect the battery pack from these hazards and maintain the safety and reliability conditions of the battery pack. The main functions of the BMS are measurement of battery voltage, current and temperature, estimation of battery state of charge (SOC) and state of health (SOH), battery cell balancing, safety and thermal management. Among these functions, battery cell balancing is the key function to improve the cell voltage imbalance [5].

Several cell balancing techniques have been proposed, which are usually classified into dissipative and nondissipative methods [6]. The dissipative cell balancing is the simplest cell balancing method. It usually uses the resistive elements to consume the excessive energy of higher voltage battery cells. The main defects of this method are low energy conversion efficiency and high temperature rise [7]. In order to overcome the defects of dissipative cell balancing method, some nondissipative cell balancing methods have been studied. These nondissipative cell balancing circuits are usually implemented based on switched capacitors, inductors/transformers or DC/DC converters [8]. On one hand, due to the usage of inductors, transformers, or DC/DC converters, the inductor/transformer based circuit or DC/DC converter based circuit has the disadvantages of high control complexity, high cost, and large size. On the other hand, capacitor based cell balancing circuit employs capacitors as the energy transfer elements, it has the advantages of low control complexity, low cost and small size [9]. Compared with other circuits, the capacitor based cell balancing circuit is more promising [10].

For the capacitor based cell balancing circuit, some topologies have been proposed. The conventional switched capacitor (SC) circuit [11] as shown in Fig. 1(a) is the basic one among all the capacitor based cell balancing circuits. In the conventional SC circuit, charge is only exchanged between two adjacent battery cells through one capacitor within one switching period [11]. When there are only two cells in the battery string, the balancing speed is fast. However, as the battery cell number increases, the balancing speed will decrease significantly. In order to improve the balancing speed, a double-tiered SC (DTSC) circuit [12] and a chain structure of SC circuit [13] are developed. These two methods increase the balancing speed by adding more charge transfer paths. However, charge is still not able to be exchanged between any two cells directly. The balancing speed still decreases as the battery cell number increases. To overcome these problems, a series-parallel SC voltage equalizer [14] and an automatic SC cell balancing circuit [15] are proposed. By connecting the capacitors in parallel with the corresponding battery cells and all the capacitors in parallel periodically, any two battery cells can exchange charge directly in these two circuits [14], [15]. Therefore the balancing speed is improved significantly. However, the disadvantage is that the number of switches is twice of that in the conventional SC circuit. To decrease switch number, an optimized SC circuit as shown in Fig. 1(b) is proposed in [16] and a switched coupling capacitor equalizer is developed in [17]. In these two methods, charge can also be exchanged between any two cells directly, therefore the balancing speed of these two methods is the same as that of the series-parallel SC circuit [17].

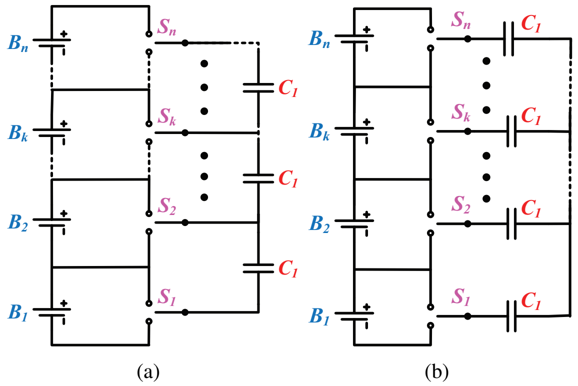


Fig. 1. Two existing capacitor based circuits. (a) Conventional SC circuit. (b) Optimized SC circuit.

To improve cell balancing speed, this paper proposes a novel SC circuit. Compared with the series-parallel SC circuit and the switched coupling capacitor equalizer, the conventional SC circuit is more suitable for two-cell battery strings [15], [17]. Based on that, the proposed circuit combines the conventional SC circuit and the optimized SC circuit. Its circuit configuration and operation principles are introduced, circuit modeling and analysis are described. Then, comparisons with the conventional SC circuit and the optimized SC circuit are given. For the proposed circuit, its balancing speed is doubled compared with the optimized SC circuit. Finally, simulation with six cases under different numbers and initial voltages of battery cells is carried out in PSIM. Simulation results show the average decrease of the balancing time is 82% and 50% compared with the conventional SC circuit and the optimized SC circuit, respectively.

II. Proposed circuit

A. Circuit Configuration and Operation Principles

The proposed circuit combines the conventional SC circuit and the optimized SC circuit. Fig. 2(a) shows the proposed circuit when the number of battery cells is even. Every two adjacent battery cells B_{i-1} and B_i (i is even) form a module. For the cell balancing between modules, each SC unit consists of a capacitor C_2 and one single pole double throw (SPDT) switch $S_{(i-1)i}$. For the cell balancing inside each single module, each SC unit is composed of a capacitor C_1 and two SPDT switches S_{i-1}, and S_i. There are n capacitors and $3n$ bi-directional switches for balancing n battery cells. When the number of battery cells is odd, the last battery is left alone after dividing the battery string into modules because each module consists of two battery cells. In this case, the proposed circuit is configured as shown in Fig. 2(b). Battery B_n (n is odd) and B_{n-1} form a module. The SC unit inside the module is made up of a capacitor C_1 and two SPDT switches S_{n-1}, and S_n. The SC unit for the balancing of the module with other modules is composed of a capacitor C_2 and one SPDT switch $S_{(n-1)n}$. $n+1$ capacitors and $3n+1$ bi-directional switches are required for balancing n battery cells when the number of battery cells is odd.

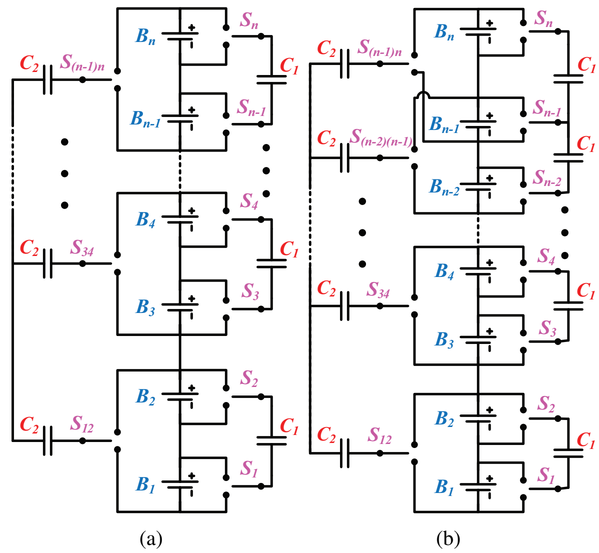


Fig. 2. Proposed circuit. (a) When the number of battery cells is even. (b) When the number of battery cells is odd.

The cell balancing between the modules is utilized by the optimized SC circuit and the cell balancing inside the module is implemented by the conventional SC circuit. The same as the conventional SC circuit, the balancing operation of the proposed circuit is controlled by a pair of complementary PWM signals. Therefore, there are two operation states of the proposed circuit within one switching cycle. Fig. 3(a) and 3(b) show the two working states of the proposed circuit when the number of battery cells is 4. In state I, two series-connected capacitors C_2 are connected in parallel with one battery module, and the capacitor C_1 is connected in parallel with one battery cell in each single module. In state II, the two series-connected capacitors C_2 are connected in parallel with the other battery module, and the capacitor C_1 is connected in parallel with the other battery cell in each single module. The two working states operate alternatively with a high frequency and the charge transfer between any two battery cells is implemented. Voltages of all the battery cells are finally equalized.

B. Circuit Modeling and Analysis

Before modeling, the following assumptions are made to facilitate the analysis: (i) the number of battery cells in the battery string is even; (ii) all the capacitors have the same capacitance C, equivalent series resistance (ESR) r_c, and all the bi-directional switches have the same on-resistance r_s; (iii) the equivalent resistance of the SC unit is R_{eq}. For the optimized SC circuit, the equivalent model is analyzed in [16]. Based on this, the equivalent model of the balancing process between modules is given in Fig. 4(a). When the capacitor is switched between two battery cells it can be regarded as a resistor connecting the two cells [18]. Hence, the equivalent

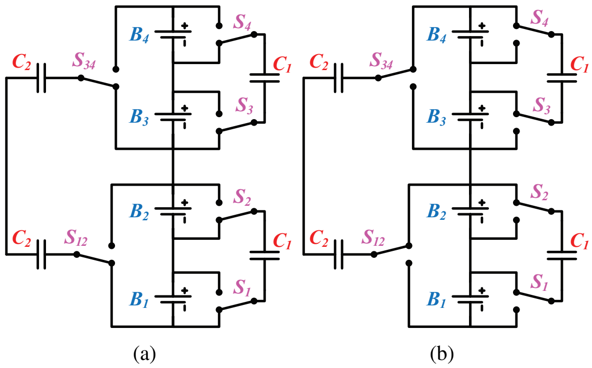


Fig. 3. Working states of the proposed circuit. (a) State I. (b) State II.

model of the balancing process between the two battery cells in the single module is derived in Fig. 4(b).

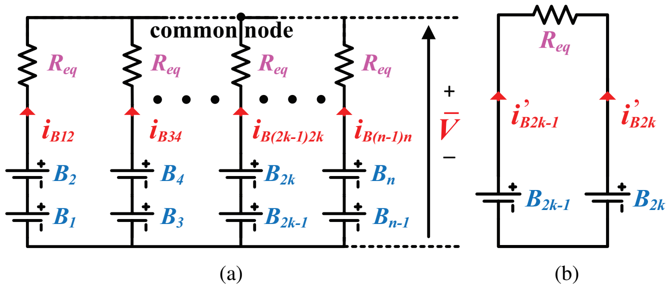


Fig. 4. Equivalent model of the proposed circuit. (a) Model of balancing process between modules. (b) Model of balancing process between the two cells in single module.

In the equivalent model of Fig. 4(a), there are n battery cells (n is even) in the battery string. B_{2k-1} and B_{2k} ($1 \leq k \leq n/2$) are two adjacent cells which form a module. The equivalent resistance of the SC unit when the duty cycle of the PWM signals equals 0.5 is expressed as [5]

$$R_{eq} = \frac{1 + e^{-\frac{1}{2rCf}}}{Cf(1 - e^{-\frac{1}{2rCf}})}, \tag{1}$$

where r is the sum of the ESR of the capacitor and the on-resistance of two bi-directional switches, i.e., $r = r_c + 2r_s$; f is the switching frequency. The voltage of the common node is fixed and can be described as

$$\bar{V}(t) = V_{B2k-1}(t) + V_{B2k}(t) - i_{B(2k-1)2k}(t)R_{eq}, \tag{2}$$

where $V_{B2k-1}(t)$ and $V_{B2k}(t)$ are the transient voltages of battery cells B_{2k-1} and B_{2k}, respectively; $i_{B(2k-1)2k}$ is the current flowing into or out of the module composed of battery cells B_{2k-1} and B_{2k}. Taking into account all the battery modules, (2) can be further rewritten as

$$\bar{V}(t) = \frac{2}{n}\sum_{k=1}^{n/2}[V_{B2k-1}(t) + V_{B2k}(t) - i_{B(2k-1)2k}(t)R_{eq}]. \tag{3}$$

Using the Kirchhoff's current law (KCL) at the common node of the equivalent model in Fig. 4(a), it can be wtitten

$$\sum_{k=1}^{n/2} i_{B(2k-1)2k}(t) = 0. \tag{4}$$

Substituting (4) into (3), the voltage of the common node is rewritten as

$$\bar{V}(t) = \frac{2}{n}\sum_{k=1}^{n/2}[V_{B2k-1}(t) + V_{B2k}(t)]. \tag{5}$$

Then, the balancing current of battery cells B_{2k-1} and B_{2k} is derived as

$$\begin{aligned} i_{B(2k-1)2k}(t) &= \frac{V_{B2k-1}(t) + V_{B2k}(t) - \bar{V}(t)}{R_{eq}} \\ &= \frac{V_{B2k-1}(t) + V_{B2k}(t) - \frac{2}{n}\sum_{i=1}^{n/2}[V_{B2i-1}(t) + V_{B2i}(t)]}{R_{eq}}, \end{aligned} \tag{6}$$

where the positive current $i_{B(2k-1)2k}(t)$ means the battery cells B_{2k-1} and B_{2k} are discharging while the negative current means the battery cells B_{2k-1} and B_{2k} are charging.

In the equivalent model of Fig. 4(b), the balancing current between the two battery cells B_{2k-1} and B_{2k} in the single module is derived as

$$i'_{B2k-1}(t) = -i'_{B2k}(t) = \frac{V_{B2k-1}(t) - V_{B2k}(t)}{R_{eq}}. \tag{7}$$

By taking into account the balancing processes between and inside the modules, the balancing current of battery cells B_{2k-1} and B_{2k} can be derived as

$$\begin{aligned} i_{B2k-1}(t) &= i_{B(2k-1)2k}(t) + i'_{B2k-1}(t) \\ &= \frac{2V_{B2k-1}(t) - \frac{2}{n}\sum_{i=1}^{n/2}[V_{B2i-1}(t) + V_{B2i}(t)]}{R_{eq}}, \end{aligned} \tag{8}$$

$$\begin{aligned} i_{B2k}(t) &= i_{B(2k-1)2k}(t) + i'_{B2k}(t) \\ &= \frac{2V_{B2k}(t) - \frac{2}{n}\sum_{i=1}^{n/2}[V_{B2i-1}(t) + V_{B2i}(t)]}{R_{eq}}. \end{aligned} \tag{9}$$

(8) and (9) can be further rewritten as

$$i_{B2k-1}(t) = 2\frac{V_{B2k-1}(t) - \frac{1}{n}\sum_{j=1}^{n}V_{Bj}(t)}{R_{eq}}, \tag{10}$$

$$i_{B2k}(t) = 2\frac{V_{B2k}(t) - \frac{1}{n}\sum_{j=1}^{n}V_{Bj}(t)}{R_{eq}}. \tag{11}$$

Combining (10) and (11), the balancing current of battery cell B_i $(1 \le i \le n)$ is derived as

$$i_{Bi}(t) = 2\frac{V_{Bi}(t) - \frac{1}{n}\sum_{j=1}^{n} V_{Bj}(t)}{R_{eq}}. \tag{12}$$

Based on the analysis, it can be seen that any two battery cells in the battery string can exchange charge during one switching cycle. Consequently, the balancing speed is increased significantly compared with the conventional SC circuit.

III. Comparison with the Conventional SC Circuit and the Optimized SC Circuit

A. *Comparison on Circuit Configuration and Operation principles*

The capacitor number, switch number and capacitor stress of the proposed circuit and the existing capacitor based circuits when the battery string consists of n battery cells is shown in Table I. For the existing capacitor-based circuits, the switch stress is $V_{B\_\max}$, and for the proposed circuit, it is $2V_{B\_\max}$, where $V_{B\_\max}$ is the maximum voltage of single battery cell.

TABLE I
Comparison on Capacitor Number, Switch Number and Capacitor Stress of the Proposed Circuit with the Existing Circuits.

Balancing Circuits	Number of Capacitors	Number of Switches	Capacitor Stress
SC	$n-1$	$2n$	$V_{B\_\max}$
DTSC	$2n-3$	$2n$	$2V_{B\_\max}$
Chain structure SC	n	$2n+4$	$V_{B\_\max}$
Series-parallel SC	n	$4n$	$V_{B\_\max}$
Automatic SC	n	$4n-3$	$V_{B\_\max}$
Optimized SC	n	$2n$	$(n-1)V_{B\_\max}/2$
Proposed circuit (n is even)	n	$3n$	$(n-2)V_{B\_\max}/2$
Proposed circuit (n is odd)	$n+1$	$3n+1$	$(n-2)V_{B\_\max}/2$

For the conventional SC circuit, the capacitors are switched back and forth periodically during the balancing process [11]. Charge is merely transferred from one battery cell to its adjacent battery cell within one switching period [11]. When there are lots of battery cells in the battery string, charge exchange between the first cell and the last one has to go through all the cells and capacitors [17]. Consequently, as the battery cell number increases, the balancing time of the conventional SC circuit will increase significantly. In the optimized SC circuit, one terminal of each switched capacitor is connected to the corresponding switch and the other terminal is connected to a common node [16]. When the switches are turned back and forth, any two battery cells can exchange charge directly through two series-connected capacitors. Therefore, the balancing speed is improved significantly compared with the conventional SC circuit.

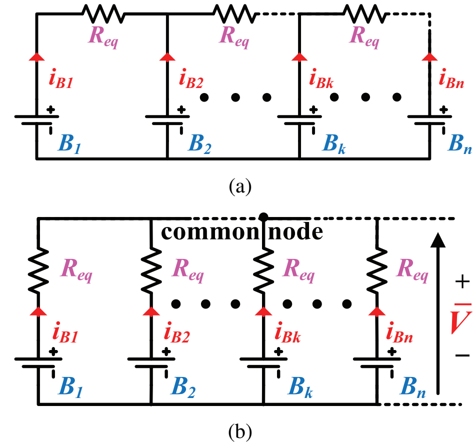


Fig. 5. Equivalent models of two existing capacitor based circuits. (a) Model of the conventional SC circuit. (b) Model of the optimized SC circuit.

B. *Comparison on Equivalent Model and Balancing Speed*

The capacitor can be regarded as a resistor connecting two battery cells when it is switched between the two cells [18]. Therefore, the equivalent model of the conventional SC circuit is derived in Fig. 5(a). The equivalent resistance R_{eq} between two adjacent cells is the same as (1). For battery cells B_i and B_j, the equivalent resistance between them is $(j-i)R_{eq}$, where $j > i$. The larger the resistance is, the lower the balancing speed is. Therefore, as battery cell number increases, the balancing speed of the conventional SC circuit will decrease. Fig. 5(b) shows the equivalent model of the optimized SC circuit. In this model, the equivalent resistance between any two battery cells is $2R_{eq}$, where R_{eq} is the same as (1). Consequently, the balancing speed of the optimized SC circuit is independent of battery cell number increase. The average voltage at the common node of the model and the balancing current of battery B_k $(1 \le k \le n)$ are expressed as [16]

$$\bar{V}(t) = \frac{1}{n}\sum_{j=1}^{n} V_{Bj}(t), \tag{13}$$

$$i_{Bk}(t) = \frac{V_{Bk}(t) - \bar{V}(t)}{R_{eq}} = \frac{V_{Bk}(t) - \frac{1}{n}\sum_{j=1}^{n} V_{Bj}(t)}{R_{eq}}, \tag{14}$$

where $V_{Bk}(t)$ is the transient voltage across battery cell B_k.

Comparing (12) with (14), it can be seen that the balancing current of each battery cell in the proposed circuit is double of that in the optimized SC circuit under the same conditions. This means the balancing speed of the proposed circuit is twice that of the optimized SC circuit.

IV. Simulation Results

The simulation of the proposed circuit compared with the conventional SC circuit and the optimized SC circuit is carried out in PSIM for four-cell, five-cell and eight-cell battery strings. In the simulation, battery cells are regarded as capacitors to decrease the simulation time [13]. Each

SPDT switch is composed of two N-channel MOSFETs, and a pair of complementary PWM signals are used to control the balancing operation. In order to limit the current spike of capacitors, the parasitic resistance is neglected [16]. The simulation parameters are shown in Table II. Six cases are conducted and the battery cell initial voltages are listed in Table III. Case I, II and III are used to compare the balancing speed under different numbers of battery cells while case IV, V and VI are used for comparing the balancing speed under different initial voltages of battery cells.

TABLE II
SIMULATION PARAMETERS.

Parameter	Value
Switching frequency [kHz]	50.0
Duty cycle	0.5
Battery cell capacitance [F]	1.0
Switched capacitor capacitance [μF]	100.0

TABLE III
INITIAL VOLTAGES OF BATTERY CELLS.

Cases	V_{B1} (V)	V_{B2} (V)	V_{B3} (V)	V_{B4} (V)	V_{B5} (V)	V_{B6} (V)	V_{B7} (V)	V_{B8} (V)
I	3.60	3.55	3.48	3.42	—	—	—	—
II	3.60	3.55	3.48	3.42	3.31	—	—	—
III	3.60	3.55	3.48	3.42	3.31	3.45	3.57	3.41
IV	3.30	3.40	3.50	3.60	3.55	3.49	3.38	3.32
V	3.60	3.32	3.32	3.32	3.32	3.32	3.32	3.32
VI	3.58	3.58	3.58	3.58	3.58	3.58	3.58	3.30

The results of the cell balancing operation during 1.00 second are shown in Fig. 6 and 7. Fig. 6 illustrates the results under different numbers of battery cells while Fig. 7 shows the results under different initial voltages of battery cells. In order to facilitate the comparison of the balancing speed, the definition of standard deviation σ is used to determine the state of balancing, and defined as [7]

$$\sigma=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(V_{Bi}-\bar{V})^2}, \tag{15}$$

where n is the number of battery cells, V_{Bi} is the cell voltage and $\bar{V}$ is the mean of V_{Bi}. When $\sigma \le 0.005$ V, the battery cells are considered to achieve balance [7]. Fig. 8(a) and 8(b) show the comparison of balancing time in the six cases.

Fig. 8(a) indicates that as the number of battery cells increases, the balancing time of the conventional SC becomes longer gradually while the balancing time of the optimized SC almost does not vary. For the proposed circuit, it has faster balancing speed compared with the conventional SC circuit and the optimized SC circuit. The balancing speed almost does not vary with the increase of battery cell number. Compared with the optimized SC circuit, the balancing time of the proposed circuit is reduced to the half. The simulation results are consistant with the aforementioned analysis.

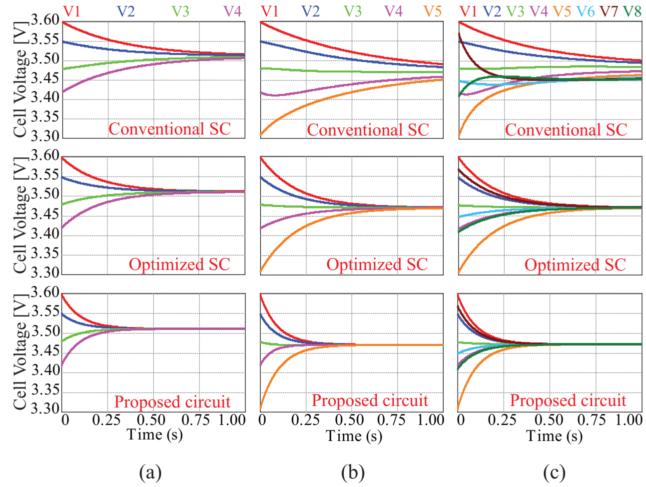


Fig. 6. Simulation results under different numbers of battery cells. (a) Case I. (b) Case II. (c) Case III.

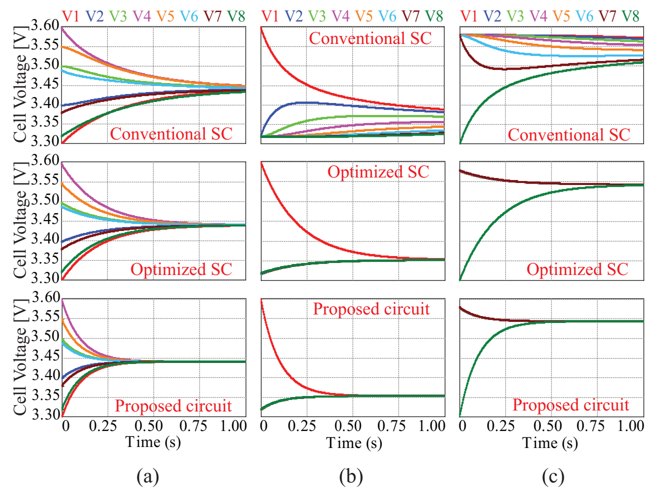
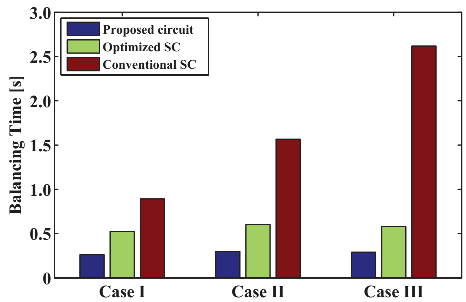


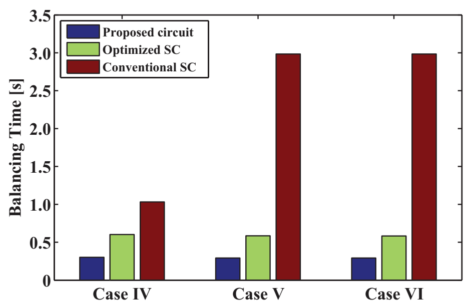
Fig. 7. Simulation results under different initial voltages of battery cells. (a) Case IV. (b) Case V. (c) Case VI.

Fig. 8(b) shows the balancing time of the conventional SC varies and the balancing time of the optimized SC is almost constant as the initial voltages of battery cells change. The balancing speed of the proposed circuit is the fastest among three circuits and the balancing time is almost invariable as cell initial voltages vary. Again, comparing with the optimized SC circuit, the balancing time is reduced by 50%, and it is also consistant with the aforementioned analysis.

Overall, the balancing speed of the proposed circuit is significantly faster than that of the conventional SC circuit and the optimized SC circuit. Compared with the conventional SC circuit, the average decrease of the balancing time is 82% in the six cases. Compared with the optimized SC circuit, the balancing speed of the proposed circuit is doubled. In addition, the balancing speed of the proposed circuit is independent of the increase of cell number as well as the variation of cell initial voltages.



(a)



(b)

Fig. 8. Comparison of balancing time. (a) Balancing time under different quantities of battery cells. (b) Balancing time under different initial voltages of battery cells.

V. CONCLUSION

In this paper, a novel SC circuit is proposed to improve battery cell balancing speed. It combines the conventional SC circuit along with the optimized SC circuit. Equivalent model of the proposed circuit is established and analyzed. Comparative analysis shows the balancing speed of the proposed circuit is twice that of the optimized SC circuit. Simulation with six cases is carried out in PSIM. Simulation results show the proposed circuit can increase the balancing speed significantly compared with the conventional SC circuit. The balancing time of the proposed circuit is reduced to the half comparing with the optimized SC circuit under both different numbers and different initial voltages of battery cells. In addition, the balancing speed of the proposed circuit is independent of cell number increase and cell initial voltage variation. The balancing time is averagely decreased by 82% and 50% compared with the conventional SC circuit and the optimized SC circuit in six cases, respectively.

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