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# A Novel Symmetrical Extensible Battery Balancing Circuit Based on Inductor

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## Summary

This paper presents a novel symmetrical extensible battery balancing circuit (SEBBC). The battery string is divided into two groups, which allows the dynamic adjustment of the equalization path. Simulation results demonstrate that the SEBBC is faster than Inductor–Based Bidirectional Lossless Equalization Circuit (IBBLEC) [1] when there are 8 cells or more. And the number of inductors for the SEBBC is less than the IBBLEC. So the SEBBC can achieve better equalization speed with less inductors.

*Keywords*: *battery strings*, *equalization speed*, *inductor*

## 1. Introduction

With the advantages of high energy ratio, long service life, high rated voltage, and low density, lithium batteries become the mainstream power battery for electric vehicles. However, due to the limited voltage of a single cell, a number of batteries must be connected in series and in parallel to form battery packs to meet the voltage and power requirements of the electric vehicles and energy storage power stations. Because of manufacturing inconsistencies, differences in the operating temperature and unique performance characteristics of each single cell, the cells connected in series may suffer from a serious imbalance between cell voltages after many charging and discharging cycles [2]. The imbalance will become more serious with the increase of charge and discharge cycles, which greatly reduces the available capacity of the battery and shortens the lifetime. Therefore, the equalization for battery strings needs to be realized. In this case, a large number of battery equalization circuits are proposed [1~10]. Unfortunately, there are few circuits that can equalize quickly with a small amount of energy storage components [3]. The IBBLEC has good equalization speed, but the number of its inductors is one more than the number of its batteries. So if there are a large number of batteries in the string, the number of inductors for the IBBLEC will be extraordinarily large and the cost will be high as well. To solve this kind of problem, this paper proposes the SEBBC. It configures an inductor for 4 cells and configures three inductors for 8 cells. And the SEBBC achieves better equalization speed with less inductors when there are 8 cells or more, compare to the IBBLEC.

The circuit structure and the equalization principle of the SEBBC are introduced in Section 2. In Section 3, the simulation results and comparison between the SEBBC and the IBBLEC are presented, followed by the conclusion in Section 4.

## 2. Proposed Circuit

### *A. Structure of the Proposed Equalizer*

Fig.1 shows the structure of the SEBBC and the IBBLEC with 4 cells. As shown in Fig.1a, the batteries in the equalization circuit are respectively named $B_{l1}$, $B_{l2}$, $B_{r1}$ and $B_{r2}$; the inductor is named $L_1$; The switches are respectively named $S_{l1}$, $S_{l2}$, $S_{r1}$ and $S_{r2}$. Each switch in the SEBBC is composed of 4 MOSFETs.

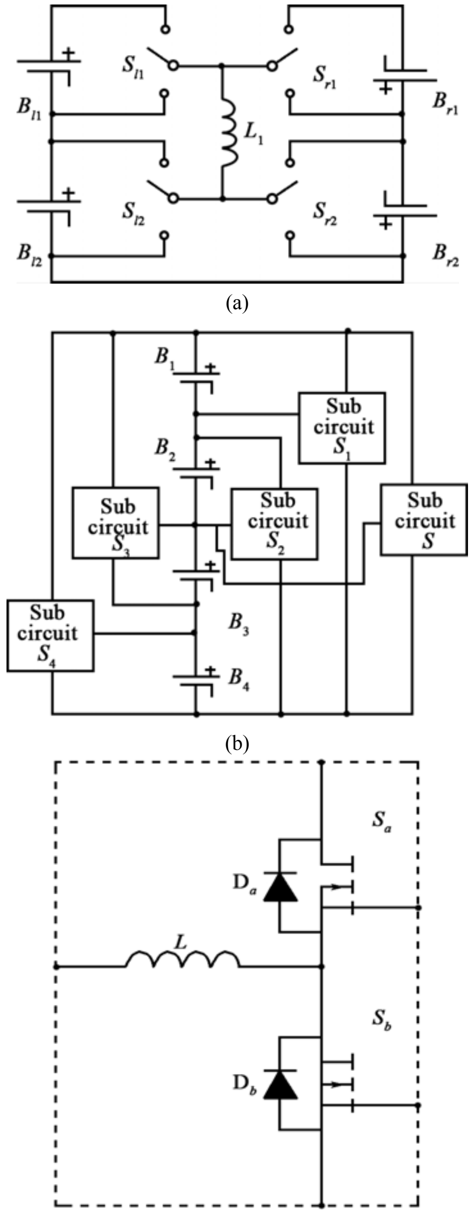
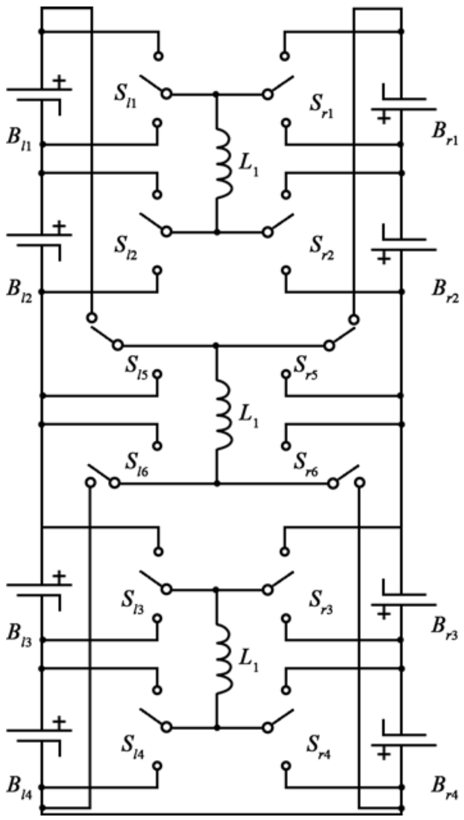
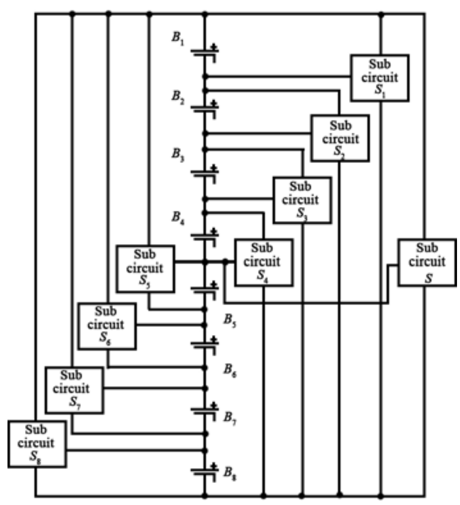



**Figure 1.** The structure with 4 cells. (a) The SEBBC (b) The IBBLEC (c) The structure of Sub–circuit

Fig.2 shows the structure of the SEBBC and the IBBLEC with 8 cells. As shown in Fig.2a, the battery string is divided into two groups, which allows the dynamic adjustment of the equalization path. The batteries in the equalization circuit are respectively named $B_{l1}$~$B_{l4}$ and $B_{r1}$~$B_{r4}$; the inductor is named $L_1$~$L_3$; The switches are respectively named $S_{l1}$~$S_{l4}$ and $S_{r1}$~$S_{r4}$ [4]. The SEBBC can be expanded to any even numbers of cells [5, 6]. When the battery number of the SEBBC is $n$ or $n$ +2, the number of inductors is $n/2$ ($n$=4$k$+2, $k$ is a non–negative integer).



(a)



(b)

**Figrue 2.** The structure with 8 cells. (a) The SEBBC (b) the IBBLEC.

### *B. Equalization Principle*

Taking 4 batteries as an example to explain the equalization principle of the SEBBC. Assuming that $B_{l1}$ has the highest voltage and $B_{r2}$ has the lowest voltage. The equalization principle with two consecutive stages is shown in Fig.3 [2]:

Stage 1: charge $L_1$

As showed in Fig.3a, in a PWM cycle, when $S_{l1}$ and $S_{l2}$ are turned on, cell $B_{l1}$ charge inductor $L_1$, $i_{L1}$ increases linearly [1].

$$V_{Bl1} = R_{on} i_{L1} + L\frac{di_{L1}}{dt},\ 0 < t < t_{on} \tag{1}$$

Where $R_{on}$ represents the loop total circuit resistance when $S_{l1}$ and $S_{l2}$ are turned on, L represents the inductance value of $L_1$, $i_{L1}$ represents the inductor current of $L_1$, $t_{on}$ represents the turn–on time of $S_{l1}$ and $S_{l2}$.

When $t$=$t_{on}$, the circuit current $i_{L1}$ reaches the maximum value $i_p$, that is:

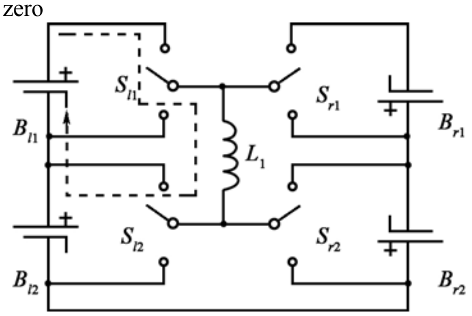
$$i_{L1} = i_p = \frac{V_{B2}}{R_{on}}\left(1 - e^{-t_{on}\frac{R_{on}}{L}}\right),\ t = t_{on} \tag{2}$$

Stage 2: discharge $L_1$

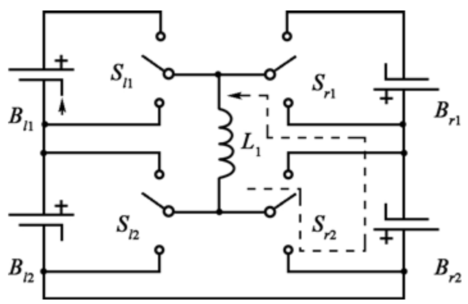
As shown in the Fig. 4b, when $t$>$t_{on}$, turned off $S_{l1}$ and $S_{l2}$, meanwhile turn on $S_{r1}$ and $S_{r2}$. $L_1$ charges $B_{r2}$ to achieve energy transfer from cell $B_{l1}$ to cell $B_{r2}$ [7].

$$i_{L1} = i_p e^{-(t-t_{on})\frac{R_{off}}{L}} - \frac{V_{Br2}}{R_{off}}\left(1 - d^{-(t-t_{on})\frac{R_{off}}{L}}\right),\ t_{on} < t \le t_d \tag{3}$$

where $R_{off}$ represents the loop total circuit resistant when $S_{r1}$ and $S_{r2}$ are turned on, $t_d$ represents the moment that inductor current falls to zero



(a)



(b)

**Figure 3.** The equalization Principle of proposed circuit.
(a) charge $L_1$, (b) discharge $L_1$

## 3. Simulation Results

In this paper, PSIM9.0 is used for simulation. 10F capacitors are employed to substitute battery cells. The switching frequency is 10 kHz. The Inductor is 33 μH. The duty cycle of PWM is 40%. During simulation, the capacitors, inductors, and switches used are considered ideal devices while ignoring the effects of parasitic capacitors and parasitic inductances. This paper uses the cells terminal voltages as the index of inconsistency because it is more easily implemented and more common [8, 9, 10].

### *C. Equalization Simulation for SEBBC and IBBLEC with 4 Cells*

Because SEBBC and IBBLEC are both affected by the initial distribution sequence of the battery, so all the distributions of the 4 batteries will be simulated and compared. The number of different distribution sequences of the four batteries is 4!=24, of which 12 samples are independent. The initial voltage of the 4 batteries is shown in Table 1, and the equalization threshold is 3mV.

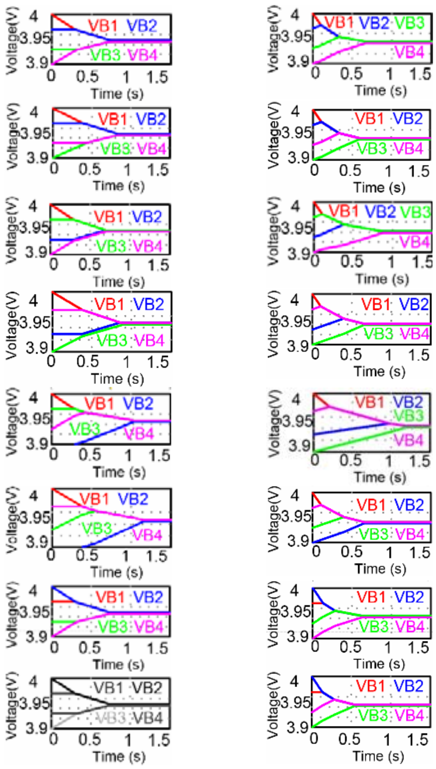
**Table 1.** The initial cell voltages of 4 batteries(voltage unit: V)

| | A | B | C | D |
|---|---|---|---|---|
| Voltage | 4 | 3.97 | 3.93 | 3.9 |

Fig.4 presents the cell voltages trajectories in SEBBC and IBBLEC. Table 2 shows the 12 independent samples and their balancing time in SEBBC and IBBLEC. Table 3 shows the comparison between SEBBC and IBBLEC in 4 cells battery string. In the 12 independent samples, the expected balancing time of the IBBLEC is 24.64% shorter than the SEBBC in average, but the proposed equalizer SEBBC uses 4 inductors less than the IBBLEC and it is greatly reduces the volume of the circuit.

**Table 2.** The balancing time in different distribution sequence for SEBBC and IBBLEC (time unit: second)

| | **ABCD** | **ABDC** | **ACBD** | **ACDB** |
|---|---|---|---|---|
| SEBBC | 0.729 4 | 0.831 9 | 0.702 4 | 0.888 0 |
| IBBLEC | 0.676 9 | 0.590 0 | 0.875 4 | 0.652 5 |
| | **ADBC** | **ADCB** | **BACD** | **BADC** |
| SEBBC | 1.036 8 | 1.155 4 | 0.732 6 | 0.737 5 |
| IBBLEC | 0.589 7 | 0.655 1 | 0.627 5 | 0.539 9 |
| | **BCAD** | **BDAC** | **CABD** | **DABC** |
| SEBBC | 1.040 1 | 0.710 2 | 0.760 1 | 1.145 1 |
| IBBLEC | 0.975 2 | 0.544 9 | 0.760 0 | 0.912 4 |



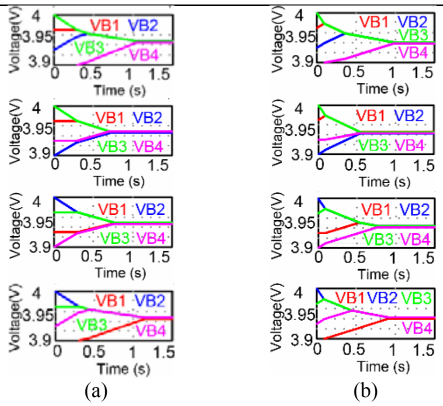




**Figure 4.** 4 cells in simulation. (a) SEBBC (b) IBBLEC.

**Table 3.** The comparison between sebbc and ibblec in 4 cells battery string.

| | **Expected Time(s)** | **Inductor** | **MOSFET** |
|---|---|---|---|
| SEBBC | 0.872 5 | 1 | 16 |
| IBBLEC | 0.700 0 | 5 | 10 |

### *D. Equalization Simulation for SEBBC and IBBLEC with 8 Cells*

We built balancing circuits for SEBBC and IBBLEC to compare the equalization speed between them with an 8 cell battery string. The initial voltage of the 8 batteries is shown in Table 4, and the equalization threshold is 3mV. The number of different distribution sequences of the eight batteries is 8!=40 320, of which 20 160 samples are independent. In this paper, we chose 100 random samples to simulation.

**Table 4.** The initial cell voltages of 8 batteries(voltage unit: V)

| | A | B | C | D |
|---|---|---|---|---|
| Voltage | 4 | 3.98 | 3.96 | 3.94 |
| | E | F | G | H |
| Voltage | 3.92 | 3.9 | 3.88 | 3.86 |

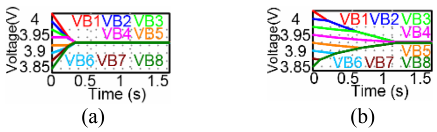



**Figure 4.** 8 cells in simulation. (a) The SEBBC (b) the IBBLEC.

**Table 5.** The comparison between SEBBC and IBBLEC in 8 cells battery string

| | **Expected Time(s)** | **Inductor** | **MOSFET** |
|---|---|---|---|
| SEBBC | 0.968 5 | 3 | 48 |
| IBBLEC | 1.541 2 | 9 | 18 |

Fig. 4 presents the cell voltages trajectories in SEBBC and IBBLEC with the distribution sequences of ABCDEFGH. Table 5 shows the comparison between SEBBC and IBBLEC in 8 cells battery string. As is shown in Table 5, in the 100 independent samples, the expected equalization time of the SEBBC is 37.16% shorter than the IBBLEC in average. The proposed equalizer SEBBC uses 6 inductors less than the IBBLEC and it greatly reduces the volume of the circuit.

The number of different and independent distribution sequences of the sixteen batteries is more than one thousand billion, so it is omitted in this paper. However, according to 100 random samples in simulation of 16 cells, the balancing time of SEBBC is also shorter than the IBBLEC in average.

## 4. Conclusion

In this paper, a novel symmetrical extensible battery balancing circuit (SEBBC) is proposed. The simulation comparisons for SEBBC and IBBLEC with 4 and 8 cells are presented. The simulation results show that the expected equalization time of the IBBLEC is 24.64% shorter than the SEBBC in average with 4 cells. But the expected equalization time of the SEBBC is 37.16% shorter than the IBBLEC in average when there are 8 cells. The SEBBC uses 4 inductors less than the IBBLEC in 4 cells, and uses 6 inductors less than the IBBLEC in 8 cells. Furthermore, as the number of batteries increases, the difference in the number of inductors used by the SEBBC and the IBBLEC will also increase, so the superiority of the SEBBC in the circuit volume is also increasing. In summary, the SEBBC achieves better equalization speed with less inductors when there are 8 cells or more, compare to the IBBLEC. The hardware platform is under construction and a large number of experiments will be conducted to verify the superiority of the SEBBC.

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