Synthesis of Balancing Topologies for Parallel-connected Battery Cells by Principle of Duality

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Abstract - In electric vehicle and battery energy storage system, battery cells are connected in parallel to prolong the working time. However, the current of each battery cell is unequal due to the imbalance of battery impedance and varied state-of-charge (SOC) rate. As a result, problems with reliability and safety may occur and battery capacity is not fully utilized. To eliminate the imbalance issue, this paper proposes two balancing methods which are transformed from series balancing techniques by the principle of duality. They use the switching capacitor circuit in ring and star structure to transfer energy from a high SOC cell to a low one. To verify the proposed method, simulations for 4 parallel-connected 18650 battery cells (3.7V/2.6Ah) have been implemented in Matlab/Simulink.

Keyword: Duality principle, battery equalizer, state of charge (SOC), switched capacitor (SC), parallel-connected battery.

1. INTRODUCTION

To reach the required operation voltage, battery cells are connected in series. Even with the same operating condition, the characteristic of each battery cell in a series-connected network is different from each other due to the uneven battery impedance and SOC, which is called battery inconsistency. To overcome this issue, various balancing techniques for series-connected battery cells are reported in [1]. On the other hand, battery cells are connected in a parallel configuration to increase the system capacity and prolong the working time. However, just a few studies about balancing techniques for parallel-connected battery cell have been conducted, and parallel configurations are usually constructed by similar impedance battery cells relying too much on the self-balancing ability of parallel connection. Therefore, the battery inconsistency still exists and causes unequal current sharing in the parallel branch which hinders maximum utilization of the battery system.

Nowadays, battery capacity optimization is becoming a key issue in the market, which requires an effective parallel balancing as well as series balancing. The behavior of battery cells in a recent parallel application is reported in the literature [2]-[3], where the inconsistency issue becomes more serious during calendar aging as the impedance of the battery cell changes. To reduce the battery inconsistency issue, fuzzy logic control is used to automatically adjust the number of cells attached to the DC bus in accordance with the load demand and SOC rate [4]. In [5], the variations in battery resistance are monitored to identify the fault cell and disconnect it from the DC bus. They show good accuracy but the computation burdens become huge as the number of battery cell increases. What is worse, performances of both methods are heavily dependent on battery electrochemical impedance which is going to be changed by calendar aging. Thus, the parallel-connected battery network also needs a balancing mechanism which shows high performance with simple control.

However, due to the difference between series and parallel system, it is difficult to apply a series balancing technique directly to a parallel configuration. Therefore, by applying the principle of duality, this paper proposes two balancing circuits for parallel-connected battery network. The system structures are described in section 2, simulations are performed in section 3, and conclusion is made in section 4.

2. PROPOSED ARCHITECTURE

2.1. *Battery inconsistency issue in parallel battery configuration*

To understand the battery inconsistency, three parallel battery cells are modeled in Fig. 1, where the current in each battery cell is calculated by (1), (2), and (3). The modeling shows that the current in an individual cell is dependent on the open circuit voltage

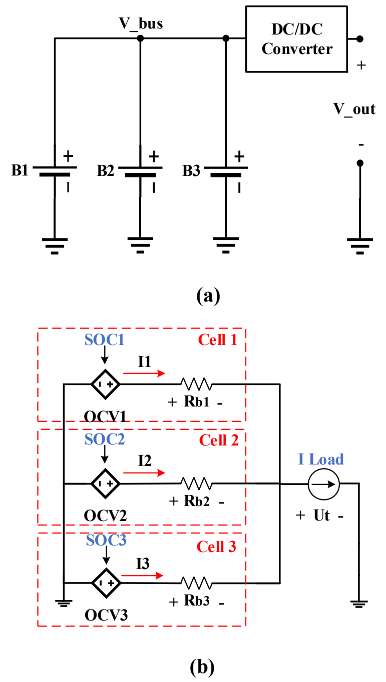


Figure 1: Parallel-connected battery network (a) three cells configuration; (b) equivalent model.

$$I_1 = \frac{I_{load} R_{b2} R_{b3}}{R_{b2}(R_{b1}+R_{b3})+R_{b1}R_{b3}} + \frac{OCV_1(R_{b2}+R_{b3}) - OCV_2 R_{b3} - OCV_3 R_{b2}}{R_{b2}(R_{b1}+R_{b3})+R_{b1}R_{b3}} \quad (1)$$

$$I_2 = \frac{I_{load} R_{b1} R_{b3}}{R_{b1}(R_{b2}+R_{b3})+R_{b2}R_{b3}} + \frac{OCV_2(R_{b1}+R_{b3}) - OCV_1 R_{b3} - OCV_3 R_{b1}}{R_{b1}(R_{b2}+R_{b3})+R_{b2}R_{b3}} \quad (2)$$

$$I_3 = \frac{I_{load} R_{b1} R_{b2}}{R_{b2}(R_{b1}+R_{b3})+R_{b3}R_{b1}} + \frac{OCV_3(R_{b1}+R_{b3}) - OCV_1 R_{b2} - OCV_2 R_{b1}}{R_{b2}(R_{b1}+R_{b3})+R_{b3}R_{b1}} \quad (3)$$

(OCV) and the impedance of the battery cell (R_{bi}). Moreover, there could be unregulated energy transfer between cells, which is called the self-balancing effect, even when there is no load demand. As a result, the inconsistency may generate additional internal heat dissipation.

2.2. *Derivation of a parallel equalizing scheme*

The principle of duality in the electrical circuit states that the solution to one circuit can be applied to its dual circuit [6]. Because series topology and parallel circuit are dual to each other, it is advisable to transform the series balancing circuit to parallel one for a new scheme development.

Among many schemes that have been published, the switched inductor cell balancing circuit [1] for a series-connected battery in Fig. 2(a) is a popular technique, which is a starting point of this derivation. The circuit becomes Fig. 2(b) when the battery cell is modeled by a voltage source, OCV, and an internal resistor, R_b. By applying the duality principle separately for phase A (when SPDT is in position A) and phase B (when SPDT is in position B) of the operation mode, each becomes the dual circuits in Fig. 2(c), where a current source, a conductance, and a capacitor are in parallel. In Fig. 2(d), the current sources, I_1 and I_2, and the parallel conductance, G_{b1}, and G_{b2}, return back to voltage sources in series with the conductances after a source transformation and merging of both circuits. Notice that a voltage source in series with a resistor describes a battery; thus, transforming the circuit to Fig. 2(e) makes the switched-capacitor circuit as the basic building block for parallel balancing.

2.3. *Proposed architectures*

Utilizing the derived building block in section 2.2, the balancing circuit I is proposed in Fig. 3, where the balancing capacitors form a ring structure and transfer energy between two adjacent cells through two phases of switching actions. Assume that $V_{b1}>V_{b2}>V_{b3}$, all the left switches (M_{1A}, M_{2A}, M_{3A}) are turned on in a phase A, while the right switches (M_{1B}, M_{2B}, M_{3B}) are turned off simultaneously. As a result, the balancing capacitors (C_1, C_2) are charged by battery #1 and #2 while the capacitor, C_3, discharges to battery #3.

In a phase B, all left switches are turned off and the right switches are turned on, the balancing capacitors, C_1 and C_2, are discharged, and the energy is transferred from the capacitors to the other battery cells while capacitor, C_3, is charged by battery #1. Between phase A and phase B, there is a deadtime interval when all switches are turned OFF to prevent switching noises and protect the capacitors. As the process is repeated, the SOCs of battery cells are balanced after a few periods of switching operation. The series switches, M_{1S}, M_{2S}, and M_{3S}, are used to prevent the self-balancing effect and individually control battery cells during the charging and discharging process. Without loss of generality, the proposed method can be applied to any number of parallel connections.

To increase the equalization speed and reduce the component count, another balancing circuit of star structure in Fig. 4 can be considered. It uses only a single capacitor and an extra switch for each parallel branch to transfer energy directly from the highest SOC cell to the lowest SOC cell. This method requires a SOC estimation algorithm to achieve the cell balancing. By opening the switches, M_{1S}, M_{2S}, and M_{3S}, alternatingly, it is possible to measure OCV of each battery cell, from which SOCs of battery cells is estimated to determine the highest and lowest SOC cell. The order is dynamically changed during the balancing process. This information can also be utilized in load

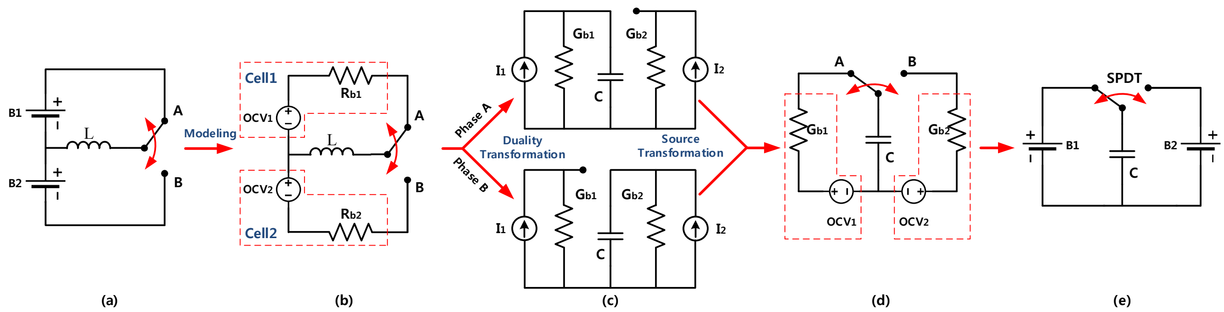
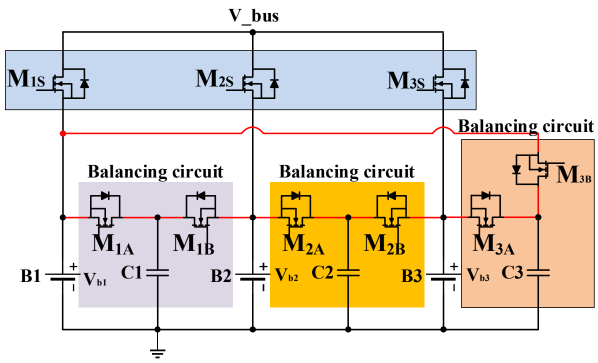
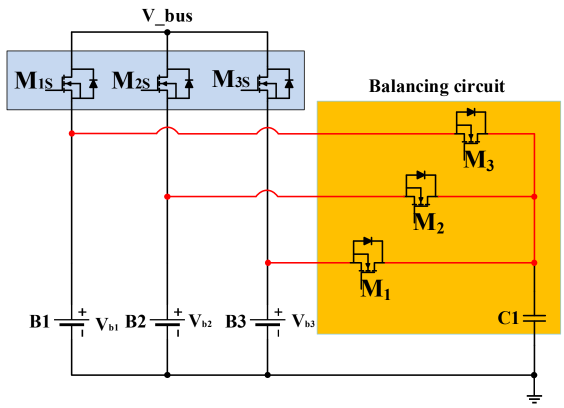


Figure 2: Duality principle transformation: (a) switched-inductor circuit for series-connected cells;(b) circuit modeling; (c) derived dual circuit; (d) dual circuit after merging; (e) switched-capacitor circuit for parallel-connected cells.





sharing so that the battery capacity is fully utilized based on the load demand. For example, the balancing process in the proposed architecture I and II can be combined with a switch scheduler which manages the series switches, M_{1S}, M_{2S}, and M_{3S}, to further maximize battery capacity utilization.

2.4. *Balancing algorithm for the proposed architecture II*

The proposed architecture II applies a SOC comparison algorithm to balance the energy of battery. Each switch M_1, M_2, M_3 can be controlled by MCU (Fig. 5(a)) signals based on the selection command from MCU.

The control flow-chart of the proposed method II is shown in Fig. 5(b). The process starts with the battery voltage measurement during a short idle duration, Tm, and the SOC of cells are estimated by OCV-SOC relationship. Once the highest and lowest SOC cells are determined through a comparison, MCU sends the corresponding PWM signal and the balancing process is executed for a period of time, Tb before the next battery voltage measurement begins. The whole process repeats until the SOC of all cells are balanced.

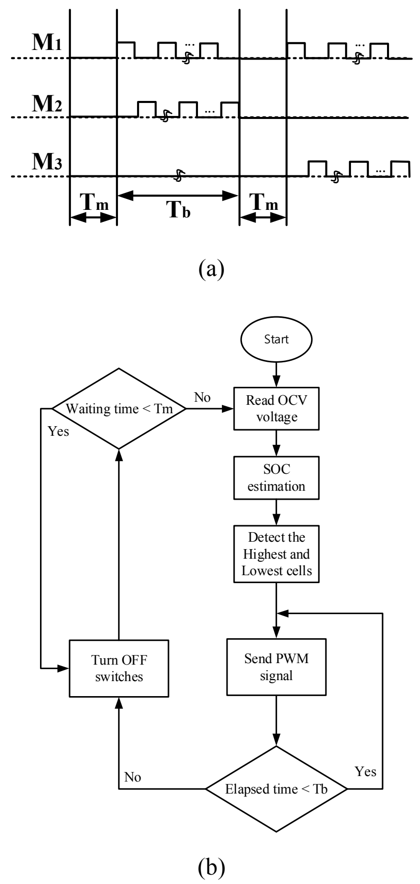


Figure 5: Control scheme: (a) timing diagram; (b) flow-chart.

3. VERIFICATION

To verify the proposed architectures, they are implemented in Matlab/Simulink for four 18650 Li-ion battery cells. The simulations are compared with the self-balancing case (without the balancing method) where batteries are connected directly altogether in parallel. It is assumed that all cells have the same capacity of 2600mAh but different initial SOCs of 100, 80, 90, and 70%. The switching frequency in the proposed method is 20kHz with a duty cycle of 45 % and the balancing capacitance is 470uF. During a few periods of switching, the SOC rate, the current and the voltage of the four battery cells are recorded in Fig. 6, Fig. 7, and Fig. 8, respectively.

For the self-balancing case shown in Fig. 6, even though there is no load demand, battery #1 has to discharge for about 6000 seconds to charge the other two cells due to self-balancing effect. At the end of the period, the SOC of battery #1 is significantly reduced and the SOCs become unbalanced (Fig. 6(a)). During the self-balancing process, battery #1 generates heat and reduces its lifetime.

On the contrary, with the proposed architecture I, the energy transfer process is regulated and the current is balanced to an appropriate level within 2000 seconds (Fig. 7(b)). After 5000 seconds, the SOCs are almost identical with the difference less than 5% in the proposed architecture I (Fig. 7(a)) and less than 2% in the proposed architecture II (Fig. 8(a)). Moreover, the required time to reach within 5% difference of SOC in the proposed architecture II (3500 seconds) is smaller than in the proposed architecture I (5000 seconds). In other words, the proposed architecture II has higher balancing speed than the proposed architecture I due to the star structure and control algorithm which transfers energy directly from cell to the other.

Although the required algorithm for the proposed architecture II is more complex due to the SOC estimation, only two cells are balanced in a period of time and the other cells are facilitated to rest during the SOC comparison, which can further prolong the lifetime of the battery.

In view of the battery cell voltages, the self-balancing method makes the voltage of battery #1 drop down dramatically. On the contrary, the DC bus and all battery voltages are well balanced with the proposed architecture I as in Fig. 7(c). In Fig. 8(c), the DC bus voltage maintains an average of all battery voltages due to the balancing algorithm. It can be observed that the self-balancing effect is completely suppressed.

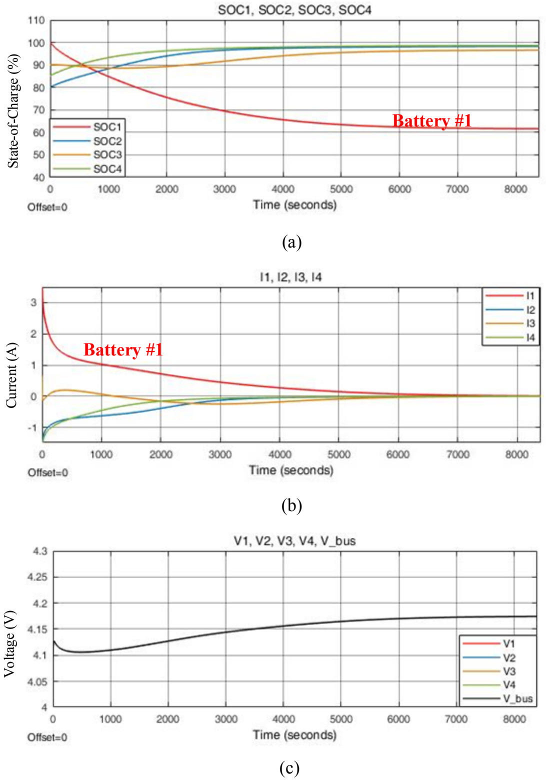


Figure 6: Simulation result – self-balancing: (a) battery SOC; (b) battery current; (c) battery voltage.

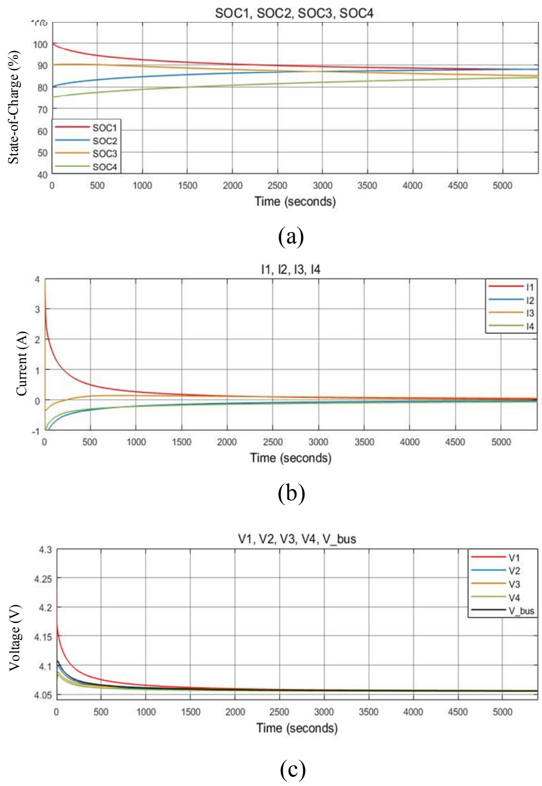


Figure 7: Simulation result – ring structure: (a) battery SOC; (b) battery current; (c) battery voltage.

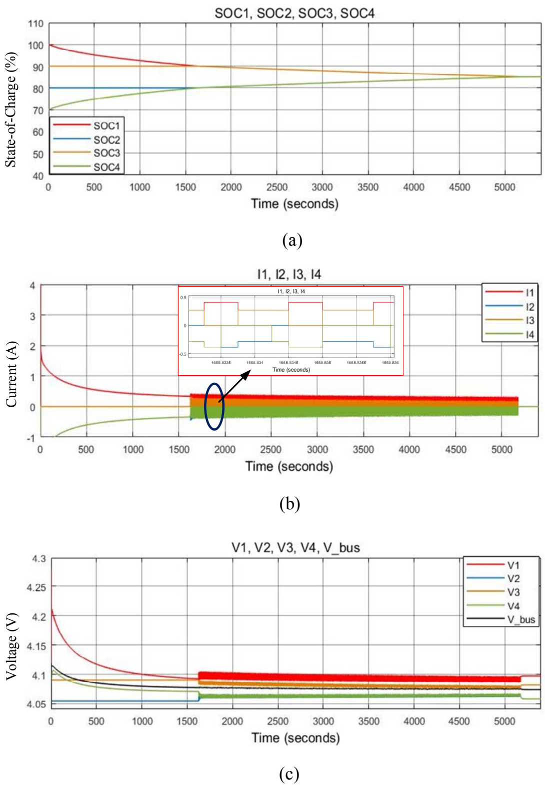


Figure 8: Simulation result – star structure: (a) battery SOC; (b) battery current; (c) battery voltage.

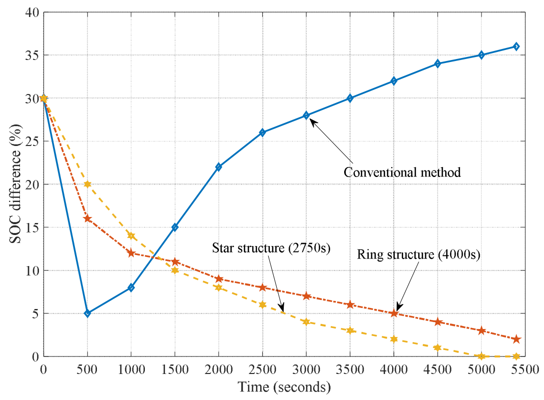


Figure 9: Comparison of SOC difference during equalization process

To evaluate the equalization performance, the SOC difference is calculated during the equalization process. The trends of SOC difference in the self-balancing and two proposed methods are shown in Fig. 9. The self-balancing equalizes the SOC fast but in the uncontrollable manner. The SOC difference becomes larger if cell #1 continuously discharge to charge the other cells. On the contrary, the equalization process in the proposed methods is controlled and the SOC difference decreases greatly after the equalization process. To reach a SOC difference of 5%, the ring structure takes about 4000 seconds while the star structure only requires 2750 seconds. Thus, it is clear that the star structure has higher equalization performance than ring structure.

4. CONCLUSION

This paper proposes two switched-capacitor balancing circuits in a ring and a star structure which evolved from series balancing technique by the principle of duality. The proposed methods use the switched-capacitor as a charge pump to transfer energy between cells and prevent the self-balancing effect in parallel connection. The simulation result shows that the SOCs of all battery cells are balanced within 5% and 2% difference after 4000 seconds by the proposed method I and II, respectively.

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