Development of voltage balancing method for series connected batteries by combination of switched capacitor and modified shunting resistor methods with series connected diodes

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Abstract. This paper proposes an alternative technique to develop battery voltage balancing methods based on the switched capacitor (SC) method by adding a modified switched shunting resistor method with the addition of several series connected diodes. The proposed technique was evaluated and compared to conventional SC method by simulation using Scilab 6.0 software, then validated based on experimental results. The simulation results show that the proposed method has better balancing speed than conventional SC method in all scenarios, in all level state of charge (SOC) variations, either in the bottom level, the middle level, or in the top level. The balancing speed of the proposed method can be increased through proper optimization on the control of the on-off duration in shunting resistor switch. Setting on duration 800 ms and off duration 200 ms can provide a fairly rapid balancing effect without excessive temperature rise, 50 °C in maximum from the initial 25 °C. Thus, the balancing method with this technique deserves to be developed further into an alternative method in developing battery balancing methods.

1. Introduction

The use of batteries in certain applications requires that some battery cells must be connected in series forming a battery module. When a charge-discharge (C-D) operation is performed on one battery module, it automatically performs a C-D operation simultaneously on a number of battery cells. While for each battery cell can not be ascertained to have the same electrical properties resulting an imbalance condition. The imbalance condition has occurred since the first time it is used because of the different conditions and electrical properties of each cell varying since the battery is manufactured [1–3]. The initial imbalance is relatively small (negligible), but it will continue to increase over time, so the voltage of one or more cells increase / drop faster than others and this case will often occur. If this condition is allowed then overcharge and over-discharge on one or more cells in battery module will occur frequently.

The overcharge and over-discharge of the battery cell should be avoided as both conditions can cause a decrease in battery performance even in certain circumstances can lead to worse damages [4–7]. Therefore balancing is a must-have in any application of series connected cells battery module and usually integrated in battery management systems (BMS) chips. Many balancing methods have been studied and proposed to overcome the imbalance problem in the battery module. Generally, the
methods are classified into two groups, namely the passive method and the active method [8]. The passive method is a balancing method by mechanism of dissipating excess energy on excessive cells using passive components such as resistors, while the active method is a balancing method that uses active components such as capacitors and inductors by mechanism of transferring energies from excessive cells to other deficient cells. The two categories have their own advantages and disadvantages, so the choices need to be adapted to the application.

One of the passive methods is Shunting Resistor method. In this method, every cell is parallel connected to one resistor. This method is very simple and does not require complicated controls and it is easy to implement because of its small size. The balancing speed can be adapted easily with the proper resistor, so it can be used to overcome the unbalance problems that require fast or slow equalization. However, from many reviews, this method is not suitable for high-power applications such as electric cars because their dissipative character can lead to overheating [8]. In addition, this type of method is considered as an inefficient balancing method.

In electric car applications, active methods based on Switched Capacitor (SC) have been widely developed. This is one of the simplest methods of many other active methods. Theoretically, this method has high efficiency and it is easy to implement because of its small size. However, this method is considered as a slow balancing method. This method has been largely developed in the hope of speeding up the equalization process [9–13]. However, those developments usually offer high complexity with the addition of many switches. So, this research tries to offer a new technique to develop balancing methods that remain to consider the simplicity in addition to increase the speed of equalization by using combination of SC methods and modified shunting resistor methods.

2. Proposed balancing method

The balancing mechanism with the proposed method consists of two parts: the active part and the passive part. The balancing mechanism on the active part is equal to the conventional SC method, so it will not be discussed further in this paper. On the other hand, the passive balancing mechanism is designed to follow the balancing mechanism of the switched shunting resistor method, but has been modified by the addition of series diodes.

The purpose of addition series connected diodes is to adjust the current output of cells by utilizing the knee voltage of the diodes and to limit minimum voltage of the cell when discharging. Another reason is the exponential characteristic of the diode current can be utilized to speed up the balancing process, meaning that with a small voltage difference between the cells, the output currents can be greater than using resistors only. The advantage of this modification is the power dissipation mechanism. The power dissipation does not only occur in resistors but also distributed evenly on each diode, so the temperature does not increase excessively.

The schematic of the proposed method can be seen in figure 1. The on/off switches are installed at the lower end of the diodes with low frequency, less than 1 Hz. The on and off periods on this switch affect the balancing speed and the temperature of the electrical components so it needs a proper adjustment. If it desired to be fast balancing, the on period is set longer than the off period, but the impact is a faster rising temperature. Thus, the on and off periods of the switches need to be adjusted to obtain a balance between balancing speed and a reasonable rising temperature.

3. Results and discussions

3.1 Simulation result

From figure 2 to figure 4 show a comparison of simulation results of the voltage balancing process between the use of proposed method and the conventional SC method. In this simulation, 4 identical cells with a capacity of 2500 mAh are modeled at first then performed balancing simulation using Scilab 6.0 with the provisions of several parameters as listed in table 1. SOC variation of each battery cell is divided into 3 parts such as the top, middle and bottom level variations. The result of a balancing simulation using conventional SC method is also included as a comparison in this study.
From figure 2, it is clear that the difference performance between the proposed method and the conventional SC method. The balancing by proposed method is much faster than the conventional SC method on top level SOC variation. So, does the SOC variation at the middle level (figure 3) and bottom level (figure 4). By using the proposed method, the curve of the 4-cell voltage values tends to narrowing faster than using conventional SC methods.

Table 1. Parameters involved in the simulation.

| Parameters            | Description |
|-----------------------|-------------|
| Capacitor             | 100 µF      |
| Switching frequency (active) | 1 kHz    |
| Switching Frequency (passive) | 1 Hz     |
| Duty Cycle switch    | 45 %        |
| Duration time        | 3600 s      |

Figure 1. Balancing mechanism of proposed method.

Figure 2. Simulation results in the top level SOC variation: (a) proposed method, (b) conventional SC method.
3.2. Experimental results

In this experiment, the balancing speed using conventional SC method and proposed method is performed on 4 identical Sony VTC5 lithium-ion cells with a capacity of 2500 mAh. The voltage of 4 cells is varied until the SOC variation is obtained at three levels at the top, middle and bottom levels. In this experiment, the provisions of these three levels are detailed as follows: the top level is the SOC level which ranges from 80 % to 100 %, the middle level is the SOC level which ranges from 40 % to 80 % and the bottom level is the SOC level which ranges from 0 % to 40 %. Implementation of proposed methods and conventional SC methods need some components as listed in table 2.

Figure 5 shows the differences in balancing performance between proposed methods and conventional SC methods. At the top level of SOC variation, the balancing speed by using proposed method is much faster than using the conventional SC method. So, does the SOC variation at the middle level (figure 6) and bottom (figure 7). By applying the proposed method, the voltage curves of four cells tend to narrowing much faster than using conventional SC methods. From figure 5 to figure 7, if its noticed, there are different curve characteristic in the 3 SOC levels, especially in the use of proposed methods. The bottom level shows voltage curves more noisy than others, may caused by the relaxing voltage gap when the switch is off tends to higher in this level as shown in figure 7 (a).
Table 2. Parameters involved in the experiments.

| Parameters               | Description     |
|--------------------------|-----------------|
| Capacitor                | 100 µF          |
| Resistor                 | 1 Ω             |
| Diode                    | UF4004          |
| Switching Frequency (active) | 1 kHz        |
| Switching Frequency (passive) | 1 Hz        |
| Duty Cycle switch        | 45 %            |
| Duration time            | 3600 s          |
| N-MOSFET                 | IRFZ44N         |
| Optocoupler              | PC817           |

Figure 5. Experimental results in the top level SOC variation: (a) proposed method, (b) conventional SC method.

Figure 6. Experimental results in the middle level SOC variation: (a) proposed method, (b) conventional SC method.

There are similarities between the simulation results and the experimental results, where the proposed method is able to reduce gap voltage values faster than conventional SC method. The comparative summary of simulation results and experimental results easily understood through table 3.
Figure 7. Experimental results in the bottom level SOC variation: (a) proposed method, (b) conventional SC method.

Table 3. Summary comparison of the capability of reducing voltage gap (by proposed method and conventional SC method) between the simulation and experimental results after 1 hour balancing process.

| SOC variation level | Simulations | Experiments |
|---------------------|-------------|-------------|
|                     | Proposed method | Conventional SC method | Proposed method | Conventional SC method |
| Bottom              | 49 mV        | 8 mV        | 93 mV        | 5 mV          |
| Middle              | 78 mV        | 8 mV        | 55 mV        | 5 mV          |
| Top                 | 81 mV        | 4 mV        | 117 mV       | 2 mV          |

4. Conclusion
Based on the simulation and experimental results it can be concluded that battery voltage balancing performance using the proposed method is generally superior to the conventional switched capacitor (SC) methods in all levels of SOC cell battery variation. Proposed method can perform faster balancing speed than conventional SC method. It is able to reduce gap voltage value up to 117 mV within 1 hour for battery cell size 18650 2500 mAh, while conventional SC method can only reduce maximum gap voltage of 5 mV.

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