A Review on the Battery Balancing and Reconfiguration Methods

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Abstract

With the development of electric vehicles, battery cells are connected in serial/parallel to cope the energy and power demand. In such serial connected battery strings, the battery imbalance is inevitable. Battery balancing and reconfiguration methods are considered as the most important methods to keep the battery string in better performance. As a results, more and more literatures have been published recently. This paper tries to give a survey of the state-of-the-art methods of the balancing and reconfiguration. Their principal features are illustrated, and the main pros and cons are provided.

Keywords: electric vehicle, battery balancing, battery equalization, reconfiguration, battery string

1. Introduction

Due to pollution and the energy crisis, research in new energy, such as electric vehicles (EVs), photovoltaic power (PV), wind power, etc., has increased worldwide\cite{1-9}. Battery energy storage systems (BESSs) are frequently used in such applications. Battery Management Systems (BMS) have been widely used to monitor the states of the battery. However, unlike the many states of the battery can not be measured directly with sensors, such states could be the State of Health (SOH) \cite{10, 11}, the State of Charge (SOC) \cite{12-14}, the State of Power (SOP) \cite{15-17}, the State of Energy (SOE) \cite{18}, and so forth. Meanwhile, to cope with the power and energy demands for such applications, a large number of battery cells, hundreds or even thousands, must be connected in a series or parallel. With so many battery cells utilized in BESSs, the cell unbalanced problem cannot be ignored.

Manufacturers have tried to select and place the same cells in a battery string, with the same state of charge (SOC), self-discharge rate, capacity, etc. However, no two cells are identical in practice, even when they are in the same production pool and the same production batch. Slight differences in these cells lead to a large mismatch after a certain period of use. Some cells may have less capacity, and these cells will hit the discharging voltage limitation earlier when discharging. As a result, the system will have to shut down the entire battery string for safety, and the good cells in the string cannot be fully discharged. Consequently, the total capacity of the battery string will decrease. The charging process is the same, in which the good cells cannot be fully charged. Treated as an entirety for the cells in the battery string, any cell can influence the entire battery string’s performance according to the “bucket effects.”

Balancing or equalization is considered as the main solution to the problem stated above, and many balancing schemes and circuits have been presented in previous studies \cite{19-23}. Balancing is sufficient when the capacities of the cells in the battery string are almost the same with only SOC differences. However, sometimes, some cells in the battery string fade faster than others and these cells own less capacity. In this situation, balancing works only when the capacity differences are small. When the differences are bigger, some cells in the string are faulted for instance, the balancing technology may not be able to make up this unevenness. Swapping the cells may be the best solution in this situation. However, cells in battery strings are normally stored in battery packs, and to swap them is very difficult, time-consuming and high-cost.

The reconfiguration technology has been proposed to improve the performance and prolong the life of BESSs \cite{24-29}, which is considered as another solution to this problem. A reconfigurable battery string provides the flexibility to connect or remove a single battery cell from the connection matrix, and multiple cells can be connected in a series, parallel, or a mixture of series and parallel configurations. Kim and Shin proposed a dynamic reconfiguration framework that reconfigures battery cells in a large-scale battery string and provides supply voltage online as needed \cite{24}. Kim et al. applied the reconfiguration of storage bank technology to a
hybrid electrical energy storage system to improve the cycle efficiency and capacity utilization [25]. Song Ci et al. proposed a dynamic reconfiguration multi-cell battery topology to improve battery performance [28]. The switch array matrix topology was developed for microbatteries and proved that the topology could transfer energy to the load without any loss of energy [30]. The reliability analysis is applied to the reconfiguration battery pack [31]. However, the disadvantage of these technologies is that many switches are needed. As a result, the drive circuits for these switches are also very complex, which may lead to reliability problems. In addition, since the importance of balancing [32], two independent systems must be added to the BESS as a result, as shown in [27], which is complex and expensive.

This paper attempt to propose a fractional equivalent circuit model for lithium-ion batteries based on frequency domain analysis. The relationship among the different order RC models and the fractional impedance model are explained.

2. The Balancing Topologies

The bidirectional buck-boost converter balancing topology is given in Figure 1, which is referred to as topology 1 in this paper [33-35]:

![Figure 1 The Bidirectional Buck-boost Converter Balancing Topology.](image)

In this method, the energy is transferred from the high energy cell to its adjacent cell through the buck-boost converter. The cell to cell balancing method is realized. For example, \( C_1 \) could be balanced by \( C_2 \) directly. However, the problem is that cells can only be balanced by their adjacent cells. If the two cells that needed to be balanced have long distance (\( C_1 \) and \( C_n \) for instance), it will take more than one steps and also long time to transfer energy between these two cells.

Figure 2 is one of the most widely used balancing topologies, and it is referred to as topology 2 in this paper [22, 36]. In this topology, a bidirectional flyback converter is connected to each cell. The secondary transformer of the converter is connected to the battery string terminals. This method transfer energy between the cell and the battery string separately. Owing to the large amount of separated converters, cells could be balanced with the battery string at the same time. Although it is a string to cell balancing method, the total balancing time could be dramatically reduced.

![Figure 2 The Traditional Bidirectional Flyback Converter Balancing Topology.](image)

However, the problem is also caused by the large amount of converters. In this case, \( 2n \) switches and \( 2n \) windings are needed for an \( n \) cells battery string. Meanwhile, since the secondary transformer of the converter is connected to the battery string terminals directly, the switches in the secondary transformer of the converter would suffer high voltage stress. Since the voltage applied to the two sides of the converter has high ratio, the transformer of the converter should have a large transfer ratio, which is nearly equal to the ratio of the two voltages. For the \( n \) cells battery string, such a ratio would be \( n \). If the primary winding of the transformer is \( m \) turns, the secondary winding should be \( n \times m \) turns. All these aspects would lead to high cost to build the circuits for such a balancing structure. Meanwhile, since the ratio of the transformer is high, the converter efficiency would be relatively low.

Figure 3 depicts another most widely used balancing topology, and it is referred to as topology 3 in this paper [34, 37-39]. In this topology, only one transformer is utilized. The transformer has \( n \) primary windings, connecting to the \( n \) battery cells, and one secondary winding, connecting to the battery string terminals.

![Figure 3 The Shared Transformer Flyback Converter Balancing Topology.](image)
Comparing this topology with topology 2, it is clear that this topology combines the $n$ separating converters to a whole converter. By this way, the switches are reduced to $n + 1$, almost half the number of switches used in topology 2. Besides, the removed $n - 1$ switches are connecting to battery string terminals in topology 2, suffering high voltage stress. Only one switch in this topology would suffer the high voltage stress. Meanwhile, the secondary windings connecting to the battery string terminals are also reduced to one from $n$. So, the cost of this topology would be dramatically reduced, compared to topology 2.

However, in this topology, only one cell could be balanced at a time and it is still a string to cell balancing method, leading to a longer balancing time comparing to topology 2. Besides, the transformer ratios are the same as those of topology 2, and the converter efficiency would be almost the same as that of topology 2.

Considering the topology 1, what if the inductors are replaced by coupled windings as those in topology 2 and topology 3. Based on the analysis of the three topologies discussed above, a new balancing topology is deduced [23], as shown in Figure 4. The novel balancing topology would reduce the number of the switches, the windings, and also the cost, but remain the full balancing functions. Meanwhile, the control signal could also be much simpler, leading to a much simpler control and drive system. Balancing between cell and battery string would lead to relatively low efficiency as stated above. In this topology, cell to cell balancing method is also realized, leading to a reduction of the balancing time and also of the complexity of control processes. Besides, only low ratio transformers are needed for the cell to cell balancing method, leading to a relatively higher balancing efficiency.

Figure 4 The Bidirectional Flyback Converter Balancing topology.

In Figure 4, $L_1$, $L_2$ to $L_n$ are coupled windings, and every two cells in the string share one of such a winding. For example, $C_1$ and $C_2$ share the same winding $L_1$. Current $I$ is the main current applied to the battery string, while $I_1$, $I_2$, to $I_{2k}$ are the balancing currents for each cell respectively. To ensure every two cells sharing a winding, the total number of cells ($n$) in the battery string are designed to be even ($n = 2k, k = 1, 2, \ldots$).

3. The Reconfiguration Topologies

The general balanced reconfiguration topology was introduced in [25] as shown in Figure 5, which is referred to as $T_1$ in this paper.

Figure 5 The general reconfiguration topology.

In Figure 5, $B_1$ to $B_n$ denote the battery cells in the battery string, and $S_i$ represents the switches. In this topology, parallel and series configurations can be achieved by controlling the switches ON or OFF. For instance, when $S_{i1}$ and $S_{i3}$ are ON, while $S_{i2}$ is OFF (where $i$ means the $i^{\text{th}}$ cell of the battery string), $T_1$ forms a parallel connection battery string. Similarly, when $S_{i1}$ and $S_{i3}$ are OFF while $S_{i2}$ is ON, $T_1$ forms a series connection. In the series connection, when $S_{21}$, $S_3$, and $S_{22}$ is ON and $S_{21}$ is bypassed. However, in the parallel connection, none of the cells is bypassed.

To solve this problem, a multi-cell battery topology was proposed [28], as shown in Figure 6, which is referred to as $T_2$.

Figure 6 The multi-cell battery topology.

In Figure 6, when $S_{i1}$ and $S_{i3}$ are ON, and $S_{i1}$, $S_{i2}$, and $S_{i3}$ are OFF, a parallel configuration is formed. Compared to $T_1$, each cell can be connected to the battery string terminal by adding two switches for each cell. Thus, any cell can be selected or bypassed when in parallel connection. For instance, in the parallel configuration, when switch $S_{24}$ or $S_{25}$ is OFF, $B_2$ is bypassed. When a series configuration is needed, $S_{i1}$ and $S_{i2}$ should be ON, while $S_{i1}$, $S_{i3}$, and $S_{i5}$ should be OFF. In a series configuration, when $S_{24}$ or $S_{25}$ is OFF, $B_2$ is bypassed. A series configuration, when switch $S_{i1}$, $S_{i2}$ should be ON, while $S_{i1}$, $S_{i3}$, and $S_{i5}$ should be OFF. In a series configuration, $B_k$ (k=2…n) must be bypassed, and $S_{i(k-1)2}$ must be OFF while $S_{i(k-1)3}$ should be ON. Especially, when $B_1$ must be bypassed, $S_{i4}$ should be OFF while $S_{24}$ should be ON.

Similarly, the switch array matrix topology, referred to as $T_3$, has also been studied to achieve these functions, as shown in Figure 7 [29, 30].

Figure 7 [29, 30]
The topologies analyzed above are effective when cells in the battery string are failed and bypass is needed. However, when normal unbalancing is occurred, which is becoming increasingly important according to application feedback [40, 41], the balancing is needed. However, the methods stated above cannot own both the balancing and the reconfiguration functions. Kim shared the same topology as shown in Figure 9, which took advantage of an additional DC-DC converter for balance [27]. However, adding balancing as an additional independent function costs a lot and adds to the system complexity, not only for controlling but also for driving circuits.

The reconfigurable balancing topology, which is able to reconfigures and balances battery cells [7], as shown in Figure 10.

In this topology, $n$ cells are connected in series, and the cells in the battery string are denoted as $B_1$ to $B_n$, and the fuses as $F_1$ to $F_n$. $Fs$ is the string fuse or service fuse for the battery string, which is designed for smaller nominal current than the other fuses. Since the switches in this topology are chosen as MOSFET, they are denoted as $M_1$ to $M_n$. Each cell with a fuse and MOSFET is called as a cell module in this paper, taking $B_2$, for example.

4. The Control Strategies

The balancing methods can also be categorized as the voltage based balancing strategy (VBBS) [42, 43], the SOC based balancing strategy (SBBS) [23] and capacity based balancing strategy (CBBS) [32, 44]. The VBBS is the most utilized method since the voltages of the cells in the battery string can be measured and the accuracy could be guaranteed. However, since the relationship between the voltage and the SOC is relatively flat that even large SOC differences may lead to small voltage difference, especially for the middle-SOC section. The balancing may only be used in the low-SOC or high-SOC section, which is relatively short comparing to the middle-SOC section. As a result, the balancing circuits should own bigger capacity in order to balancing the battery in a short time, which will dramatically increase the cost and system complex. The SBBS was proposed to solve the problem stated above. However, the SOC cannot be measured directly, and errors always exist with SOC estimation method. To consider the state of health (SOH) of the battery, the CBBS was also utilized. However, the CBBS should obtain both the SOC and the
SOH of the cells in the battery string, and the resulting capacity may have large error, which will accordingly cause large balancing error.

To take advantage of the merits of both the VBBS and the SBBS, the hybrid criterion based balancing strategy (HCBBS) for BESS is proposed in [45].

5. Conclusion

Battery imbalance is crucial for many applications of batteries, especially for serial connected battery strings. This paper reviews the balancing and reconfiguration methods. The principles and features of each method are recalled and compared in this work.

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Reference


