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Review of Novel Battery Balancing Topologies

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Abstract

Imbalances in battery cells attributed either to the cell production process variability or the operating conditions of the battery, (Conway, 2020) result in the degradation of the overall performance of battery systems and can decrease their life span. Several factors such as the over-voltage, under voltage, overcharge and under charge of battery cells affect the capacity of battery cells. So, several balancing methods have been developed to preserve batteries from damaging and to expand the battery life. The present paper is a brief review about some of the state-of-the-art topologies for battery management systems (BMS). Also, a comparison table is presented. Comparison factors are the circuit design, the balancing speed, the complexity, the efficiency, the cost of production and the size of the presented topologies.

1 Introduction

Sustainable transportation and electric vehicles (EVs) have witnessed an exceptional growth in recent years. The environmental crisis along with the technological development has led to the necessity for more sustainable solutions in transportation. EVs use batteries as fuel and these batteries have to align with strict specifications in order to be environmentally friendly and energy efficient at the same time. Based on the application several types of batteries can be used in EVs such as Lead-acid, Nickel based, and Li-ion (Innovation, 2024). EVs batteries can be connected in series to increase voltage or/and in parallel to increase capacity.

Batteries' performance degrades over the years due to several factors such as temperature, over charging and over discharging, aging, mechanical stresses and etc. (Dinh, 2024). Battery management systems (BMSs) have been developed to monitor and to equalize the charge of battery cells in a battery pack protecting the users and the battery system from damages and increasing the battery life by maintaining the operational conditions in a reliable level (Daowd, 2011).

Two main balancing methods have been developed to overcome battery cells imbalances. The passive balancing method and the active balancing method. The present paper is focused on the active cell

* Writing – original draft preparation, writing – review, editing and visualization

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balancing methods. In active cell balancing, active elements such as capacitors and/or inductors as well as converters are used to transfer energy from the higher energy cell(s) to the lower energy cell(s). The active cell balancing method includes five main subcategories which are: cell bypass, cell-to-cell, cell-to-pack, pack-to-cell and cell-to-pack-to-cell depending on how the energy is transferred among the battery cells of the pack. Many topologies can be found into the literature for the battery balancing methods (Conway, 2020), (Dinh, 2024), (Moghaddam B., 2019), (Pham, 2020), (Shang Z. C., 2019), (Vivert, 2023). Figure 1 depicts how the active balancing methods and their topologies are classified.

This paper discusses the most state-of-the-art topologies and how they provide progress on the overall battery performance, speed of charging, the cost and other factors that are important in a BMS. Also, a comparison table presents a summary between the characteristics of the most recent topologies based on factors like balancing speed, complexity and size of the design and production cost.

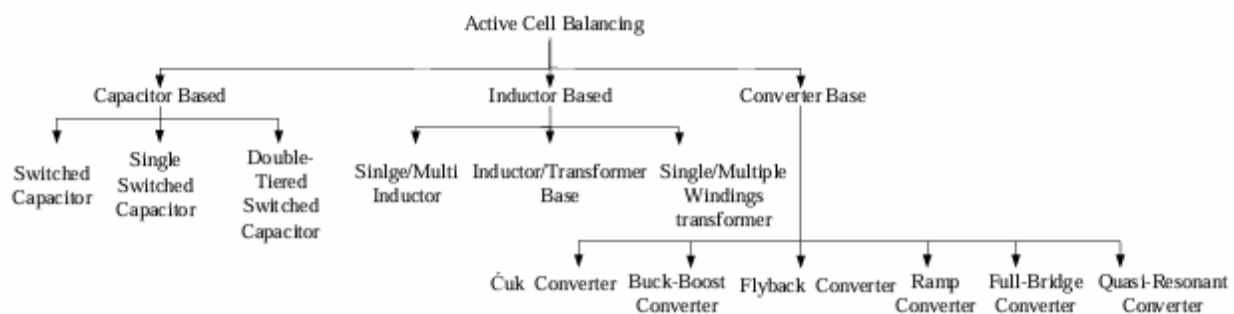


Figure 1: Classification of active cell balancing methods

2 Active Balancing Methods

The active balancing method uses elements such as capacitors, inductors or converters to transfer charge from cells with higher energy to the cells with lower energy. So, the cells in the battery pack become balanced to the same voltage level by delivering the excess charge from the cells with higher voltage levels to the lower voltage cells. The advantages of this method over the passive is that it balances the cells in shorter time and with higher efficiency levels but the topologies of the active method are more complex. Based on their transfer energy elements, active cell equalization topologies can be categorized in capacitive based, inductor or transformer based and converter based.

2.1. Capacitor Based Active Balancing Method

In this active equalization technique capacitors are used for charge transferring. The charge is stored in the capacitor from the cell with the higher voltage and transferred to the cell with the lower voltage. The capacitive based balancing topologies can be classified in the single switched capacitor, multiple switched capacitors and the double-tiered capacitor. An optimized version of the multiple switched capacitor topology is presented in (Shang Z. C., 2019). The topology is based on the Delta-Structured Switched Capacitor (DSSC) structure offering high balancing speed and high efficiency levels. The structure for every pair of two neighboring cells requires one capacitor and two series connected transistors for each cell. Figure 2 presents the DSSC structure. Accordingly, another optimized topology based on the DSSC topology has been proposed in (Singirikonda, 2021). It is a Closed-Loop Switched Capacitor Structure aims to maintain the constant voltage across each cell. The voltage of each cell is being sensed and compared with

a reference voltage and if the voltage of the cell is lower than the reference voltage then the switch is turned on. The procedure is repeated until the cell be balanced. It appears a more compact design, lower cost and very good balancing speed compared to other switched capacitor topologies (Pascual, 1997), (Kim, 2014), (Ye C. F., 2017).

The topology in (Baughman, 2008) which is presented in Figure 3 is based on the double tiered topology and proves how this structure is better in terms of equalization time, efficiency and balancing currents. Another topology that uses the double tiered switched capacitor method is realized in (Ye L. L., 2019) with improved balancing speed and reduced number of required switches making the structure suitable for industrial applications. The proposed topology is a combination of two tiers, as shown in Figure 4. Buck-boost and switched capacitor-based cell balancing techniques are combined.

2.2. Inductor Based Active Balancing Method

Inductor based topologies use inductors to transfer energy among the cells of the battery pack. There are two categories in this method, the single and the multi inductor. An inductor based topology is presented in (Moghaddam B. , 2018) tries to solve the problem of conventional inductor based balancing method that occurs when energy is transferred from the first cell to the last cell of the pack which causes delay in the balancing procedure. Also, in (N, 2020) the proposed structure operates well under charging, discharging and idle regime of battery and can easily be configured for even or odd cell battery packs. This structure is similar to (Moghaddam B., 2018) but it has faster equalization time and less number of components. Figure 5 shows the topology for four cells but it can also be extended to an odd number of cells.

Correspondingly, to single/multi inductor based topologies there are also single and multi transformer topologies. Many topologies have been proposed with single/multi winding transformers. (Moghaddam B., 2019) proposed a multi-winding transformer which compared to the common methods reduces the number of required secondaries and so the size and the cost of the design. In (Conway, 2020) the proposed topology is based on the single transformer per cell balancing method. The architecture provides effective voltage monitoring and cell balancing. The proposed equalizer utilizes four interface units, as show in Figure 6.

2.3. Energy Converters for Active Cell Balancing

Many different converter topologies are used for cell balancing. The main topologies are cuk converter, buck/boost, flyback, ramp, full-bridge and quasi-resonant converter. A cuk converter topology is proposed in (Moghaddam V. d., 2019). The proposed converter requires n switches and $n+1$ inductors for n cells which leads to less losses and to higher efficiency levels. A simplified circuit of the cuk converter with two cells is depicted in Figure 7.

In cell balancing systems the buck, the boost and the buck-boost converters are used widely. The main drawback of these converters is their high cost of production and their complex design. A buck-boost converter topology for cell balancing has been proposed in (Liu, 2020) and appears high balancing speed, high efficiency levels, compact size and low cost. The buck-boost converter is presented in Figure 8. Also, in (Raeber, 2021) a high efficiency buck-boost converter is presented which is a combination of a non-isolated DC-DC converter and a low-speed switching matrix with balancing efficiencies over 90% and it is shown in Figure 9.

A flyback converter topology is proposed in (Moghaddam V. d., 2019) and is depicted in Figure 10. The structure provides better efficiency results over the conventional flyback converter as it consists of N secondaries for N battery cells and one switch reducing losses. The full-bridge converter is mainly used for the plug-in hybrid EVs and requires intelligent and complex control method to control the switches but it depicts high power rating. A cascaded full-bridge multilevel converter is presented in (Vivert, 2023) and shown in Figure 11. The proposed work gives the ability to the converter to reconfigure by inserting and removing cells during operation. The topology is a good choice for high power applications. Finally, quasi-resonant converter is a DC-DC converter which not require any complex algorithm to operate. It has high balancing efficiency levels but it also, has high cost of production. An optimized structure of the quasi-resonant converter is proposed in (Shang Z. C., 2015) where the balancing time is reduced. Only one balancing converter is shared by all cells reducing the size of the circuit and the production cost. The core of the proposed equalizer which is a quasi-resonant LC converter is depicted in Figure 12. Another high efficiency LLC resonant converter topology is proposed by (Pham, 2020). The charge is transferred from the highest voltage cell to the lowest voltage cell using a LLC resonant converter which controls the power delivery among the selected cells and a switch network that selects the cells that are need to be balanced. It has simple design, fast balancing time and achieves a maximum efficiency of 94.5%. Figure 13 shows the structure of the proposed LLC resonant converter without the switch network.

3 Comparison

Table 1 is a comparison table among all of the state-of-the-art topologies that has been mentioned and analyzed in the present paper. The comparison factors are the balancing speed, the complexity of the design, the efficiency, the cost and the size of each topology. The significance of each of these metrics varies according to the final application. For example, in automotive systems complexity and the cost of production is an important factor. On the contrary, in military systems or Energy Storage systems the cost is not an important factor as the efficiency of the final product. So, based on the application requirements and specifications there is a tradeoff between these metrics. Therefore, BMSs are a key factor in battery cell balancing as they monitor the safe operation of the battery pack to increase the performance and the cycle life of the battery cells.

Topology	Type of Balancer	Balancing speed	Complexity	Efficiency	Cost	Size
Shang Z. C., 2019 (Fig.2)	Capacitor Based	good	simple	excellent (94%)	low	small
Singirikonda, 2021	Capacitor Based	very good	simple	excellent (95%)	low	small
Baughman, 2008 (Fig.3)	Capacitor Based	-	-	-	medium	-
Ye L. L., 2019 (Fig.4)	Capacitor Based	excellent	simple	-	low	small
Moghaddam, 2018	Inductor Based	very good	medium	-	high	-
N, 2020 (Fig.5)	Inductor Based	very good	simple	-	-	-
Moghaddam, 2019	Inductor Based	good	medium	high	low	small
Conway, 2020 (Fig.6)	Inductor Based	good	simple	medium	-	-
Moghaddam, 2019 (Fig.7)	Converter	very good	-	medium	low	medium
Liu, 2020 (Fig.8)	Converter	excellent	-	excellent (96%)	medium	small
Raeber, 2021 (Fig.9)	Converter	good	simple	excellent (90%)	-	small
Moghaddam V. d., 2019 (Fig.10)	Converter	very good	simple	high	low	small
Vivert, 2023 (Fig.11)	Converter	medium	medium	medium	-	-
Shang Z. C., 2015 (Fig.12)	Converter	excellent	-	excellent (98%)	low	small
Pham, 2020 (Fig.13)	Converter	very good	simple	excellent (94.5%)	medium	-

Table 1: Comparison Table of Active Cell Balancing Topologies

4 Conclusions

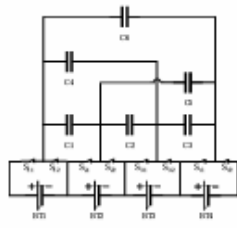


Figure 2: DSSC

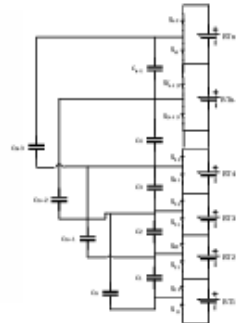


Figure 4: Double-Tiered Topology

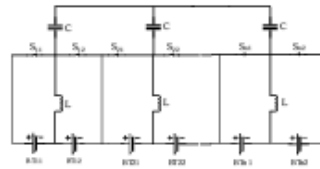


Figure 5: Inductor based Topology

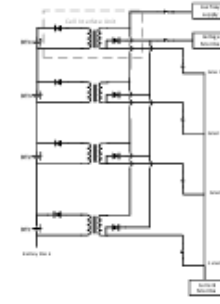


Figure 6: Single Transformer per cell Topology

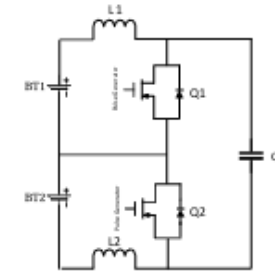


Figure 7: Simplified Cuk Converter Circuit with Two cell Topology

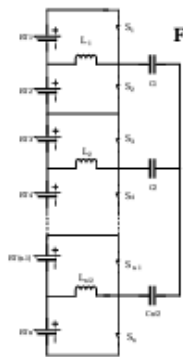


Figure 3: Double Tiered Switched Capacitor

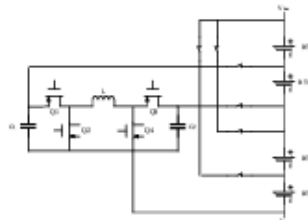


Figure 9: Buck-Boost Converter and Switch Matrix

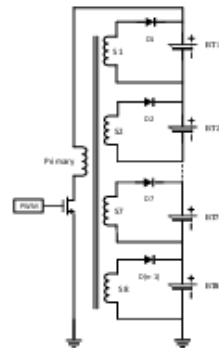


Figure 10: Flyback Converter

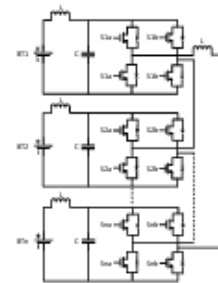


Figure 11: Cascaded Full-Bridge Converter

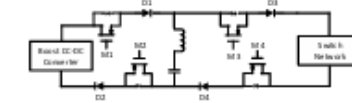


Figure 12: Quasi-Resonant LC Converter

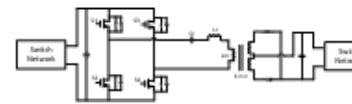


Figure 13: LLC Resonant Converter

The global demand for more environmentally friendly solutions and circular economy has increased the necessity for more efficient designs in BMSs. Future research in BMSs has to be focused on the optimization of the active cell balancing techniques to increase batteries' overall performance and to extend their life cycle. Various smart and efficient methods must be introduced to enhance batteries' efficiency levels according to different circumstances as BMSs can be found in many applications.

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