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Review

# Active Methods for the Equalization of a Serially Connected Lithium-Ion Battery Pack: A Review

**Longsheng Yuan [1], Tuo Ji [1] and Lijun Zhang [1,2,3,*]**

[1] National Center for Materials Service Safety, University of Science and Technology Beijing, Beijing 100083, China
[2] Innovation Group of Marine Engineering Materials and Corrosion Control, Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai 519080, China
[3] Research Institute of Macro-Safety Science, University of Science and Technology Beijing, Beijing 100083, China
* Correspondence: ljzhang@ustb.edu.cn

**Abstract:** Traditional fuel vehicles are currently still the main means of transportation when people travel. It brings convenience to their travels, but it also causes energy shortages and environmental pollution. With the development of science and technology and the popularization of green environmental protection, electric vehicles have gradually entered people's lives, greatly alleviating these problems. As a power supply device for electric vehicles, the performance of batteries directly affects various indicators of vehicles. Due to their long lifespan and high energy density, lithium-ion batteries are now the preferred source of power for electric vehicles. However, due to various factors in the manufacturing and operation of lithium-ion batteries, there are often differences among individual cells. The power balance and performance of a battery pack are closely related. Thus, battery equalization is an important standard for a battery management system to work normally, and it is also one of the various battery management application problems. This paper reviews battery equalization systems and various active equalization circuits and summarizes the working principle and research progress of each active equalization circuit. Then, various active equalization circuits are analyzed and compared, and dynamic equalization for a second-life battery is introduced to enrich this review of equalization technology. Finally, the above contents are summarized and prospected. In order to obtain the best outcomes, different equalization circuits need to be chosen for various situations.

**Keywords:** electric vehicles; lithium-ion battery; battery equalization system; active equalization circuits; dynamic equalization

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## 1. Introduction

As contemporary science and technology have improved, vehicles have also become an indispensable means of transportation in daily life, making travel more convenient. At present, fuel vehicles still occupy the majority of the automotive market. But, the increase in the number of fuel vehicles has also brought about many problems, such as increased air pollution, increased energy consumption, and so on [1]. In contrast, new energy vehicles, like electric vehicles, have positive environmental effects compared to conventional fuel vehicles [2,3]. Using electric vehicles instead of fuel vehicles is therefore one of the ways to promote sustainable development [4]. In order to reduce dependence on fossil energy and thus environmental pollution, many countries have accelerated the development of electric vehicles. Battery energy storage technology has also grown quickly as a key technology in electric vehicles [5]. Compared with traditional energy sources, battery energy storage systems have the advantages of being environmentally friendly and having good controllability [6]. The battery is a very sensitive part of an electric vehicle, so it is important to choose a good battery. As a means of energy storage for electric vehicles, batteries made of lithium ion [7–9] have longer lifespans and greater energy densities [10]. They usually appear in hybrid or purely electric vehicles [11].

Hundreds or more individual cells are connected to each other in series to make up a battery pack that satisfies the requirements of a large-capacity and high-voltage energy storage system. However, each cell's production and operation are inevitably different from each other [12], and this causes the cells connected in series to become inconsistent in terms of storing power. This inconsistency is exacerbated by time spent on active duty and different work environments. The inconsistency can directly affect the voltage and capacity of the vehicle, which can gradually reduce the function of the pack, thus reducing the pack's lifespan. More seriously, it can cause a single cell to deform or even explode [13]. The pack's inconsistent behavior is a typical issue, and we can apply battery equalization technology [14–16] to reduce this problem. Battery equalization technology is very important, and it is mainly used to reduce the power difference between each cell of a pack, so that the battery pack has good consistency. Thus, the service life of the battery pack can be extended, and the costs of battery packs can be reduced. As shown in Figure 1, battery equalization technology can be divided into two types: one is battery equalization strategies; the other is battery equalization topologies. Battery equalization topologies are reviewed in detail next.

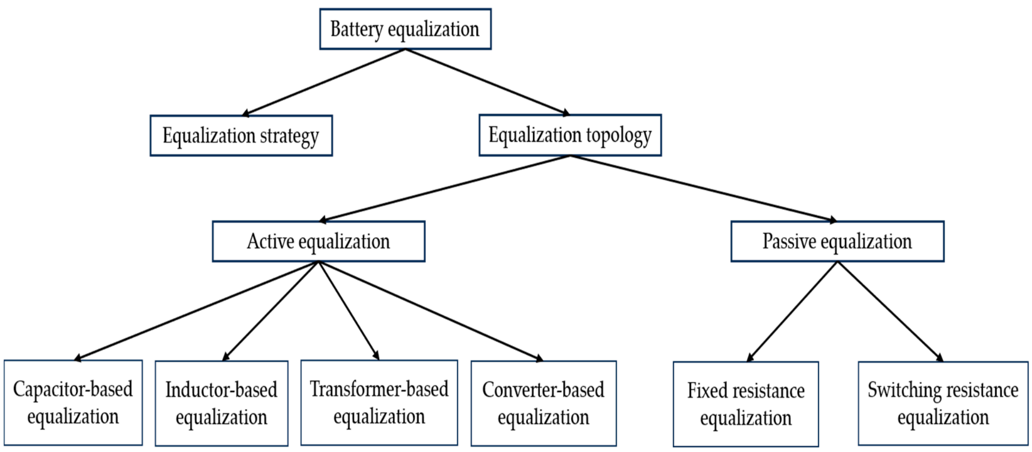


**Figure 1.** Classification of battery equalization technologies.

Many scholars have reviewed battery equalization technologies before. The number of reviews published on battery equalization is shown in Figure 2, indicating an upward trend in recent years. This trend was also proven to be significant and valuable. Reference [17] classified equalization strategies based on the equalization objectives, equalization variables, and equalization algorithms; expounded their advantages and disadvantages; and provided some suggestions for future development. Reference [18] provided a comprehensive review of different intelligent algorithms for battery management systems, including battery state estimation, battery equalization, and battery thermal management aspects. In Reference [19], the control strategy and operating principle of an active charge balance topology based on a DC–DC converter were reviewed for the first time. Reference [20] conducted a detailed analysis and comparison of active and passive equalization circuits and also studied different control methods. Reference [21] reviewed the important parts, advantages and disadvantages, and specifications of active equalization circuits.

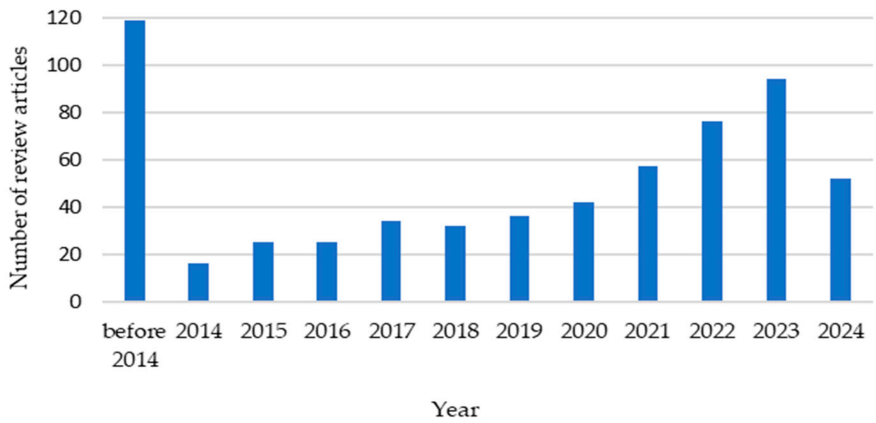


**Figure 2.** Number of review articles on battery equalization (data sources: https://www.sciencedirect.com/search?qs=Battery%20equalization&articleTypes=REV&lastSelectedFacet=articleTypes; access date: 28 March 2024).

This review provides a comprehensive introduction to battery equalization topologies based on the research of other review articles and by learning from battery equalization. The highlights of this review include the following:

- The development course of various equalization topologies are described from the perspective of vertical improvements in detail.
- The working characteristics and advantages/disadvantages of capacitor-based, inductor-based, transformer-based, and converter-based equalization topologies are explained and compared in the form of a table. And, suggestions are given on how to choose an equalization topology in practical applications.
- Dynamic equalization is introduced for second-life battery applications, and the difference between dynamic equalization and active equalization is explained.

Summaries of this paper and the above reviews are shown in Table 1 so that readers can see the difference more clearly.

**Table 1.** Summaries of this paper and some other review articles.

| Literature | Description and Comments |
|---|---|
| [17] | It mainly classified equalization strategies. But, it lacks a description of equalization topologies. |
| [18] | It mainly summarized the various algorithms of a battery management system. But, the description of battery equalization is relatively simple. |
| [19] | It reviewed the control strategy and operating principles of converter-based equalization topologies. But, it did not provide an overview of capacitor-based, inductor-based, or transformer-based topologies. |
| [20] | It conducted a detailed analysis and comparison of active and passive equalization circuits and also studied different control methods. But, it did not review the equalization topology in detail in terms of vertical improvement. |
| [21] | It reviewed the advantages, disadvantages, and specifications of active equalization circuits. However, it did not classify the topologies based on different energy storage components, and the performance comparison of various equalization topologies was not very comprehensive. |
| This review | In this paper, the equalization topology was divided into capacitor-based, inductor-based, transformer-based, and converter-based equalization topologies according to their different energy storage components. It not only details the working characteristics and advantages and disadvantages of various equalization topologies but also describes the development course of various equalization topologies from the perspective of vertical improvement. And, the dynamic equalization of a second-life battery is introduced. |

In Section 2, this paper will introduce a battery equalization system and passive equalization, and active equalization circuits based on capacitors, inductors, transformers, and converters are mainly introduced based on their various energy storage components. In Section 3, different active equalization circuits' characteristics are discussed and compared.

And, the balance speed, balance efficiency, volume, cost, and control difficulty of various active balance circuits are summarized in the form of a table. Then, the dynamic equalization of a second-life battery and its difference from active equalization are introduced. At the end of this review, the equalization circuits are summarized and prospected and some suggestions are given for the practical selection of type of equalization circuit and its future development. It provides ideas and guidance for the future innovation and development of equalization technology.

## 2. Battery Equalization System and Active Equalization Circuit Topology

### *2.1. Battery Equalization System*

As an energy management system, a battery equalization system [22–26] aims to reduce the energy differences among a battery pack's cells, thereby improving the pack's consistency. Equalization strategies and topologies are both part of battery equalization systems.

An equalization strategy refers to selecting an appropriate object as the equalization index and then using the algorithm to regulate the switch's opening and shutting according to changes in the object to achieve energy equalization of the circuit [27]. According to different equalization objects, there are three types of equalization strategies: based on residual power, based on voltage, and based on state of charge. Excellent equalization strategies can enhance the equalization circuit's efficiency and speed. Common equalization strategies include the average comparison method [28] and the fuzzy control method [29,30].

Since most equalization strategies are quite difficult to use at present and many of them are in the experimental and verification stages, this review mainly discusses battery equalization topologies. There are two forms of basic equalization topologies [31]: one is the passive equalization topology; the other is the active equalization topology. The passive equalization topology circuit depends on heat to consume extra energy in the battery. To achieve a balanced effect, some components, including resistors, are used. Due to the advantages of having a simple circuit structure and cheap price [32], in mass production, the passive equalization topology is commonly utilized. But, the goal of the passive equalization topology is to achieve equalization by consuming energy, so the energy utilization rate is greatly reduced. Therefore, the active equalization topology has gradually developed over time. Active equalization includes equalization circuits based on capacitors, inductors, transformers, and converters. Active equalization is more efficient and quicker than passive equalization. Table 2 shows the different evaluation indexes of active equalization and passive equalization.

**Table 2.** Comparison of active equalization and passive equalization.

| Type of Equalizing Circuit | Speed | Efficiency | Volume | Cost | Control Difficulty |
|---|---|---|---|---|---|
| Passive equalization circuit | Slow | Low | Small | Cheap | Easy |
| Active equalization circuit | Fast | High | Large | Expensive | Difficult |

Although passive equalization has the advantages of having a small size and being easy to control, a lot of energy is wasted compared with active equalization, so the efficiency of the equalization is very low. Nowadays, resource conservation is advocated for all over the world. Therefore, in active battery equalization research and the pursuit of better performance, a higher cost performance of battery equalization systems has become a hot research topic [33].

### *2.2. Active Battery Equalization Circuit*

The equalization topology circuit provides a route for energy transfer between the battery pack's batteries. Different from passive equalization, which dissipates excess energy, active equalization [34–38] applies an energy storage element to transfer energy among the cells. A quick equalization speed and excellent equalization efficiency are two benefits of the active equalization circuit. However, at the same time, it faces problems such as a high cost and a complex structure, and some technical problems, for which effective solutions have not yet been found [39]. Therefore, active equalization circuits are projected to face considerable challenges in the future. The active equalization circuit can be categorized depending on its various energy storage components. The most commonly used energy storage components are capacitors, inductors, transformers, and converters.

#### 2.2.1. Capacitor-Based Equalization Circuit

The switched capacitor [40] is an electronic circuit element that can be used as a filter. When the switch is turned on (off), it works by moving the charge into (out of) the capacitor and uses the capacitor's capacity for energy storage. Energy flow among the cells is achieved by using the capacitor as a transporter and adjusting the switch based on the voltage difference. The capacitor-based equalization circuit has the advantages of low energy waste and a comparatively simple design; therefore, it can be created at a smaller size and lower cost [21]. However, it is limited to transferring energy across batteries that have different voltages, less equalization efficiency results from the smaller voltage differences, and its reliability cannot be guaranteed.

Three types of capacitor-based equalization circuits exist: the single-switched-capacitor equalization circuit, the multiple-switched-capacitor equalization circuit, and the double-layer switched capacitor equalization circuit.

1. Single-switched-capacitor equalization circuit;

The single-switched-capacitor equalization circuit [41] uses a capacitor as a carrier for energy transfer. Its structure is displayed in Figure 3. B1, B2, B3 and B4 represent battery cells, and C represents the capacitor in the figure.

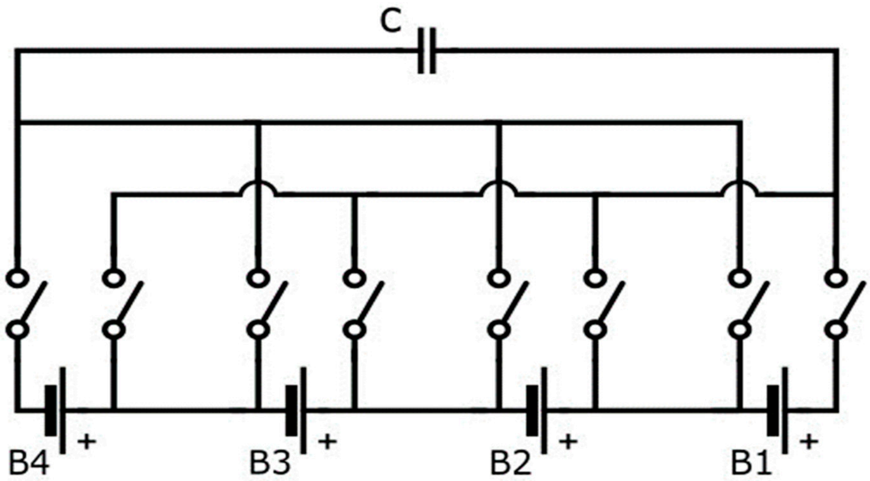


**Figure 3.** Single-switched-capacitor equalization circuit.

When a battery in the pack has an excessively high voltage, the control system recognizes it, closes the switches on both ends, and transfers its energy to the capacitor. The overly high voltage battery cell is then disconnected once the capacitor has been fully charged. At the same time, a lower voltage cell is connected to the capacitor via the closing switch and is charged by the capacitor. Energy transfer can be completed several times repeatedly to achieve balance between the battery pack's cells. The single-switched-capacitor equalization circuit's low circuit cost and easy controllability are its benefits [42]. However, this topology only allows a pair of single cells to be balanced at one time, and the overall equalization speed and equalization efficiency are not high, which is not suitable for long-battery-string equalization, so its research is limited.

2. Multiple-switched-capacitor equalization circuit;

The multiple-switched-capacitor equalization circuit provides a common capacitor for two adjacent cells and connects them with a switch. The structure is shown in Figure 4. B1, B2, B3 and B4 represent battery cells, and C1, C2 and C3 represent capacitors in the figure.

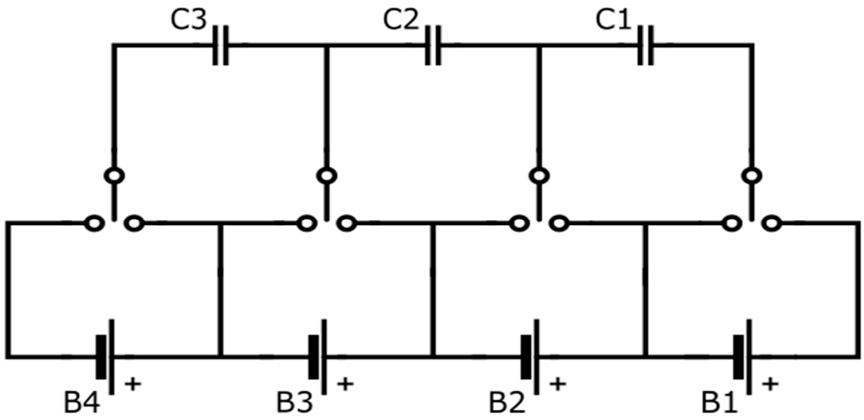


**Figure 4.** Multiple-switched-capacitor equalization circuit.

The working process is that in half of the cycle, the capacitor receives energy transfer from a higher voltage battery; in the other half of the cycle, the capacitor transfers the energy it received to a battery with a lower voltage. In the multiple-switched-capacitor equalization circuit, energy flows solely between two neighboring cells, resulting in a longer equalization time [43,44]. The multiple-switched-capacitor equalization circuit's efficiency decreases with increasing battery count. Reference [45] proposed a new structure based on the multiple-switched-capacitor circuit, which avoids difficult monitoring systems and large volumes of magnetic components. The only pulse signals required are a couple of complementary ones with a constant switching frequency and fixed duty cycle. All of the circuit's switches are under their control. The structure allows a charge to be automatically transferred from a high voltage cell to a low voltage cell, making it suitable for a circuit with lots of cells. Reference [46] proposed a switched capacitor chain structure. It is shown in Figure 5. B1, B2, B3 and B4 represent battery cells, and C0, C1, C2 and C3 represent capacitors in the figure. By the application of extra switches and capacitors, the batteries at both ends can directly exchange energy, which greatly improves the equalization efficiency. Reference [47] combined the module concept with the chain structure. In this structure, its equalization control mode is very simple, and every switch only needs to bear the voltage from one module. There is a significant improvement in the equalization effect when compared to the unadorned structure.

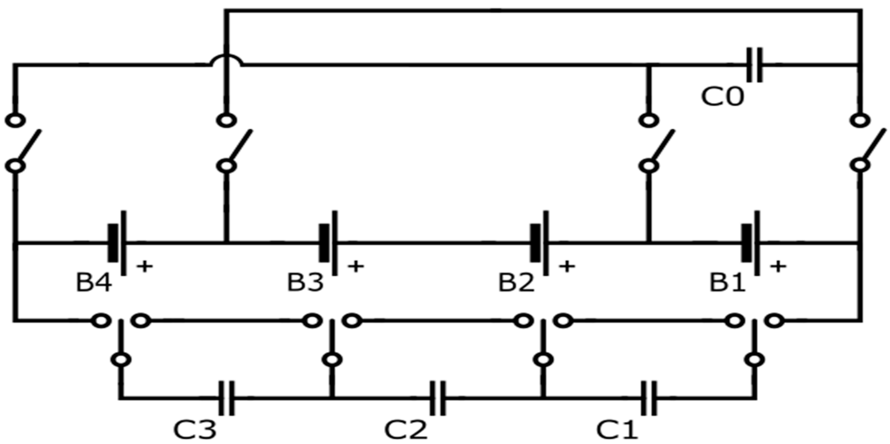


**Figure 5.** The chain structure of the capacitor.

3. Double-layer switched capacitor circuit;

A unique type of multiple-switched-capacitor circuit is the double-layer switched capacitor circuit [48]. A second layer of capacitors is added to the basic multiple-switched-capacitor circuit to accelerate the equalization process. The circuit structure is displayed in Figure 6. B1, B2, B3 and B4 represent battery cells, and C1, C2, C3, C4 and C5 represent capacitors in the figure.

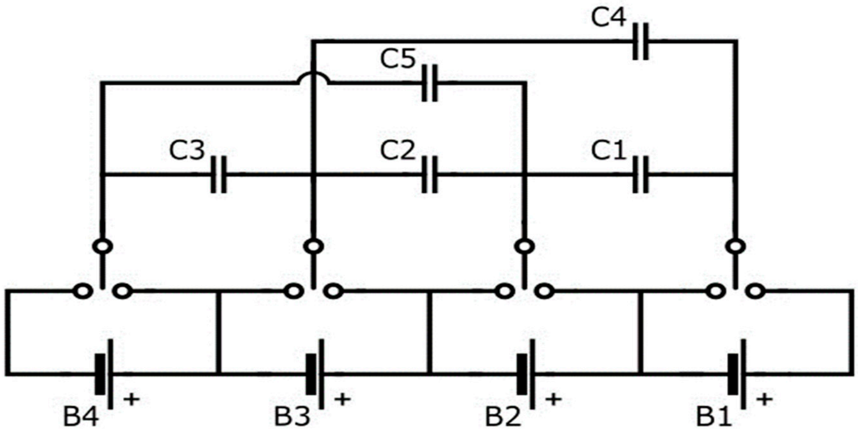


**Figure 6.** Double-layer switched capacitor circuit.

There are more pathways between the batteries if there are more layers. The energy is transmitted within neighboring cells via the first layer of capacitance, and the second layer of capacitance transfers energy between non-directly connected cells. This can reduce the equalization time. However, the circuit still cannot enable direct energy exchange between all batteries [20], and when two non-adjacent batteries perform an energy transfer, the battery between them is also involved, reducing the equalization efficiency [49]. In order to solve this problem, multi-layer switched capacitor circuits have been proposed by scholars. Reference [50] proposed a star-shaped switched capacitor circuit, which uses the least amount of capacitors and MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors) to achieve equalization between any two batteries. Without affecting the size and other factors, it achieves a high equalization efficiency independent of the allocation of battery voltage and the quantity of batteries. References [51,52] designed a class of equalization circuits with a triangular switched capacitor structure. For any two cells to have energy equalization, only two switches are required for each battery. The structure is unaffected by the quantity of batteries or the original imbalance in battery strings. The structure has high reliability and strong robustness, and it works well with circuits that have a lot of cells. Reference [53] proposed an optimized grid switched capacitor equalization structure, which obtains all the best equalization paths from one battery to another in the pack and develops switching impedance at a low switching frequency and a high switching frequency. It is shown in Figure 7. B1, B2, B3 and B4 represent battery cells, and C1, C2, C3, C4, C5, C6, C7 and C8 represent capacitors in the figure. This structure improves the equalization efficiency by up to 91.7% without increasing the circuit complexity. Due to the low voltage stress of MOSFETs, the balance system also has high reliability.

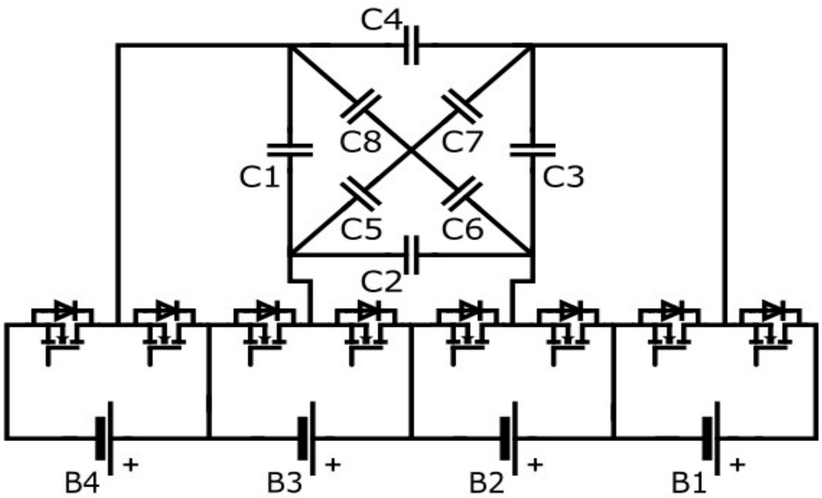


**Figure 7.** The mesh structure of a capacitor.

### 2.2.2. Inductor-Based Equalization Circuit

In the inductor-based equalization circuit [12,34], the current of the inductor cannot be changed to transfer energy among the cells. The inductor-based equalization circuit works on similar principles to the capacitor-based equalization circuit, except the components used for energy storage and transfer are changed from capacitors to inductors. There are two types of inductor-based equalization circuits: one is a single-switched-inductor equalization circuit; the other is a multiple-switched-inductor equalization circuit.

1. Single-switched-inductor equalization circuit

The single-switched-inductor equalization circuit uses a single inductor to achieve the flow of energy between cells. The switch connects the positive electrode of every cell to one side of the inductor, and the switch connects the negative electrode of every cell to the other side of the inductor in the circuits [21], as shown in Figure 8. B1, B2, B3 and B4 represent battery cells, L represents the inductor, and D1, D2, D3, D4, D5, D6, D7, D8, D9 and D10 represent diodes in the figure.

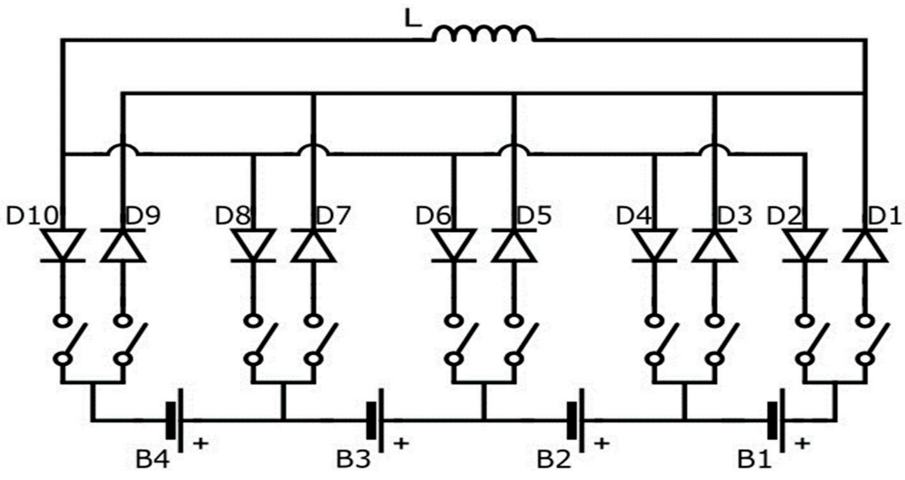


**Figure 8.** Single-switched-inductor equalization circuit.

By switching on and off, the inductor extracts energy from batteries that have a higher power, stores it, and then sends the energy to batteries that have a lower energy to complete the energy transfer. The structures are simple to use, but the cost is higher than capacitive equalization circuits [54]. The more batteries there are in the circuit, the longer it takes to equalize. It is thus not appropriate for a system with lots of batteries.

Reference [55] developed a bidirectional active equalization method based on inductance that includes several equalization paths. Any cell can transfer energy directly to another cell through a bidirectional switch with low on-loss, thereby improving the efficiency of equalization and effectively avoiding overcharging or undercharging the cells. In addition, an inductor is often used in combination with other components such as a capacitor. An active equalization method based on an inductor and a capacitor was proposed in Reference [56] by combining the advantages of the fast equalization speed of capacitor energy storage and the high equalization accuracy of inductor energy storage, which significantly improves the battery pack's consistency as a result, and thus the battery pack's overall performance. It is shown in Figure 9. B1, B2, B3 and B4 represent the battery cells, L represents the inductor, C represents the capacitor, and D, D1, D2, D3, D4, D5, D6, D7, D8, D9 and D10 represent diodes in the figure.

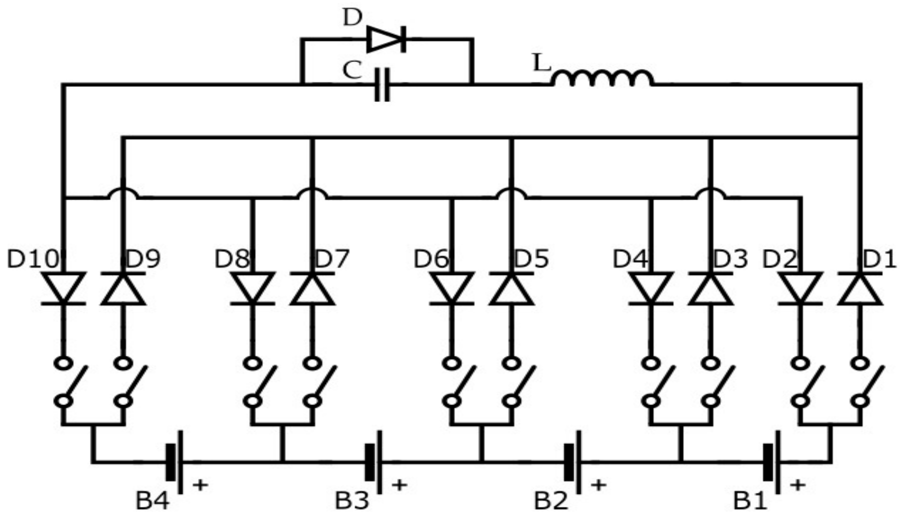


**Figure 9.** Inductor and capacitor-based equalization circuit.

2. Multiple-switched-inductor equalization circuit

In a multiple-switched-inductor equalization circuit, an inductor is placed between adjacent cells for energy storage, and the energy passes between the cells side by side through the inductor and by turning the switch on and off [57]. Its structure is shown in Figure 10. B1, B2, B3 and B4 represent battery cells, and L1, L2 and L3 represent inductors in the figure.

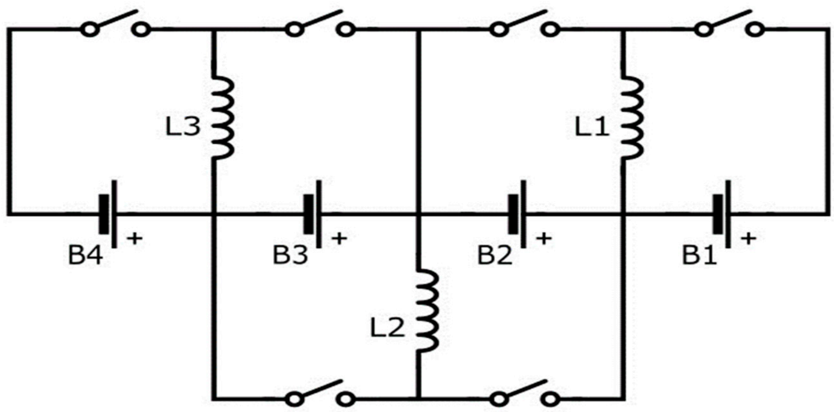


**Figure 10.** Multiple-switched-inductor equalization circuit.

This method has good scalability and a high equalization current. But, only adjacent cells can transfer energy. When the distance between the two cells to be balanced is far away, the power needs to be transferred through multiple middle inductors and the circuit needs more components. The efficiency of equalization is low as well. To overcome the above difficulties, Reference [58] proposed a topology structure that utilizes coupled inductors, and each battery was equipped with a switch and one winding for every two batteries, resulting in a significant decrease in circuit components and cost savings. Moreover, compared with traditional inductor circuits, the proposed balance structure greatly shortened the equilibrium time. It is significant to mention that an equalization circuit relying on inductors can move energy through a low voltage battery to a high voltage battery. Thus, equilibrium strategies should be carefully considered when using inductors in order to avoid mistakes [59].

#### 2.2.3. Transformer-Based Equalization Circuit

Transformer-based equalization circuits transfer energy through different modules and cells by using external transformers [60]. This type of circuit uses transformers as carriers, storing a portion of the energy from the pack or cells in the winding, transferring it to the other winding via mutual inductance, and finally transferring the energy to the pack or cells that need to be balanced through the switches. Transformer-based equalization circuits can be classified into single-winding and multi-winding circuits based on the number of transformer windings used [49]. The single-winding transformer equalization circuit has a simple structure, but its balance efficiency is low. The multi-winding transformer equalization circuit offers a fast speed and high efficiency. However, it is difficult to design, and its price is expensive. There are few applications as well.

1. Single-winding transformer equalization circuit

Every cell in the single-winding transformer equalization circuit [61,62] is linked in parallel with a set of switches, which are used in conjunction with a transformer and rectifier diodes. Its structure is shown in Figure 11. B1, B2, B3 and B4 represent battery cells, D represents the diode, and T represents the transformer in the figure.

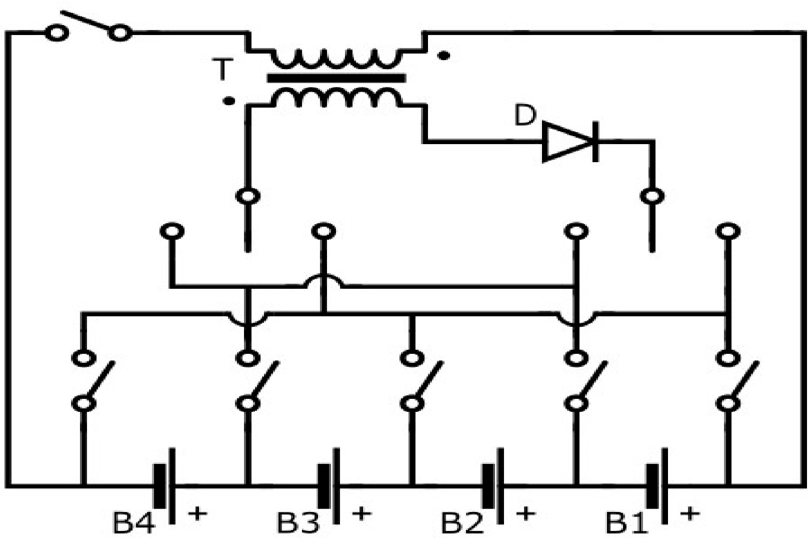


**Figure 11.** Single-winding transformer equalization circuit.

In the equalization process, a battery with a higher voltage charges the transformer's primary side. Then, the energy is coupled to the secondary side and charged to batteries with a lower voltage, thereby achieving a transfer of energy. This cycle is repeated many times, so that each single cell has essentially the same state in the battery pack, and then, power balance is achieved for every cell. The disadvantages of this type of circuit are that the equalization efficiency is low and there is only one energy transfer path. However, as compared to other circuits, the control difficulty of this circuit is low.

2. Single-core multi-winding transformer equalization circuit

The following are basic structures in a single-core multi-winding transformer equalization circuit (shown in Figure 12): an iron core, a primary winding, and a number of secondary windings. B1, B2, B3 and B4 represent battery cells, D1, D2, D3 and D4 represent diodes, and T represents the transformer in the figure.

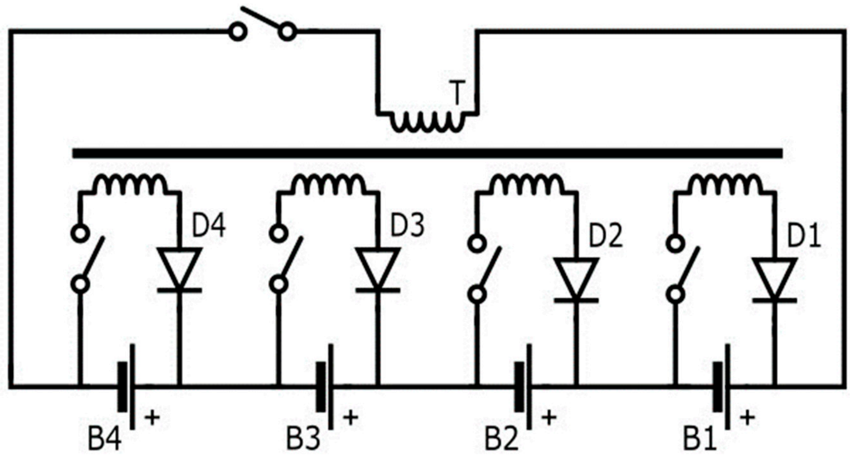


**Figure 12.** Single-core multi-winding transformer equalization circuit.

It has two modes: the flyback mode and the forward mode. In flyback mode, the transformer stores energy when the switch on one side of the primary winding is turned on; the energy is moved into the secondary winding group of the transformer when the switch is closed, and the induced current charges the battery through the diode. In forward mode, the switch connected to the battery with the highest voltage is activated upon detection of a voltage differential between individual cells, and the transformer's anti-parallel diode and switch allow the energy to be transferred to other batteries, so that the energy difference of all battery cells is kept within a certain range to prevent the single cell from overcharging or over discharging. This equalization circuit offers simple control and easy operation, but its scalability is poor. The structure of the transformer also needs to be redesigned when the battery pack's number of series cells changes.

In Reference [63], the use of a unitized multi-winding transformer as the basis for an equalization method was suggested, which achieved forward conversion and flyback conversion at the same time. The cells in the same sub-unit were equalized using the forward conversion, while the cells in different sub-units were equalized using the flyback conversion. In this structure, the battery pack's different sub-units can be balanced together, thereby improving the equalization efficiency. Reference [64] proposed a modular equalization circuit made up of a single-core multi-winding transformer. Modular equalization circuits differ from common equalization circuits in that they use a multi-winding transformer's magnetic energy to equalize modules. The circuit is not affected by factors such as size and cost related to modularization. In order to enable the transformer's stored magnetic energy to be reset by itself, a general multi-winding transformer was proposed in Reference [65] to combine the forward and flyback converters. There are two groups of windings in this transformer, and their polarities are opposite. Energy can be delivered straight from any battery that has a high voltage to any battery that has a low voltage without a battery monitoring circuit. In addition, each battery requires only a primary winding and a MOSFET, thereby decreasing the structure's size and reducing cost. The proposed topology can achieve pack equalization by connecting the transformer's secondary winding group. There is no need for additional components to balance the modules. The mismatch problem of multiple windings is thus overcome. Reference [66] provided a novel cascaded multi-winding transformer equalization circuit topology for when the number of battery packs is large. It is shown in Figure 13. B1, B2, B3 and B4 represent battery cells, D1, D2, D3 and D4 represent diodes, and T represents the transformer in the figure. This topology is less complicated in transformer structure than the common multi-winding transformer topology, making it less expensive and easier to produce.

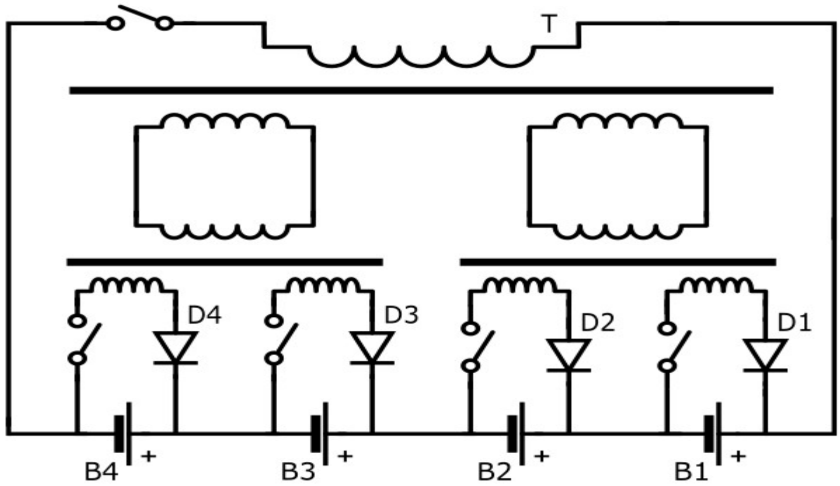


**Figure 13.** Cascaded transformer equalization circuit.

3. Multi-core multi-winding transformer equalization circuit

Each battery is connected in parallel with a transformer in multi-core multi-winding transformer equalization circuits [67]. Its structure is shown in Figure 14. B1, B2, B3 and B4 represent battery cells, D represents the diode, and T1, T2, T3 and T4 represent transformers in the figure.

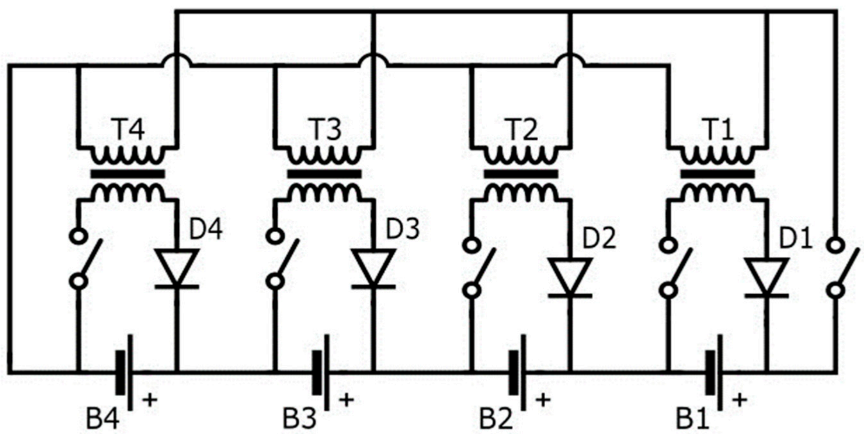


**Figure 14.** Multi-core multi-winding transformer equalization circuit.

The only thing that has to be increased is the number of transformers when the quantity of batteries connected in series rises, and the structure of the transformer does not need to be redesigned. This method's major advantage is that balance is achieved regardless of an individual cell's voltage. However, these structures require a lot of transformers, and the cost is very high. A new active equalization method for bi-directional battery-to-battery energy transfer via multi-winding transformers was presented in Reference [68]. This method allows the energy to be transmitted directly from the cell with the highest voltage to the cell with the lowest voltage through flyback or forward operations, which provides a shorter balancing path and improves the balancing speed. The circuit uses a bidirectional switch with low conduction loss to achieve efficient equalization efficiency. In Reference [69], a type of flyback conversion-based multi-core multi-winding equalizer was suggested for a series lithium-ion battery pack. During the equalization process, the modulation of the pulse width duty cycle can be varied based on with the voltage of the best charge–discharge combination, so that when the gap in voltage between the cells decreases, the equalization speed and current do not drop. It enhances the circuit equalization process' stability.

2.2.4. Converter-Based Equalization Circuit

Circuits based on a DC/DC converter to achieve battery equalization are called converter-based equalization circuits. They also use inductors, capacitors, and transformers as elements of energy storage to enable the exchange of energy among cells. Converter-based equalization circuits can transfer energy among different cells and modules. Its quick equalization speed and high integration are two benefits of this type of equalization circuit. It is also the primary direction of growth in equalization circuit research. Common converter-based equalization circuits include the Buck–Boost circuit [70], the Buck circuit [71], the Boost circuit [72], and the Cuk circuit [73].

1. Buck–Boost converter equalization circuit

The Buck–Boost converter circuit increases and decreases voltage [74]. The input voltage can be lower than or higher than the output voltage. The circuit is actually a circuit composed of multiple inductors, and its structure is shown in Figure 15. B1, B2, B3 and B4 represent battery cells, and L1, L2 and L3 represent inductors in the figure.

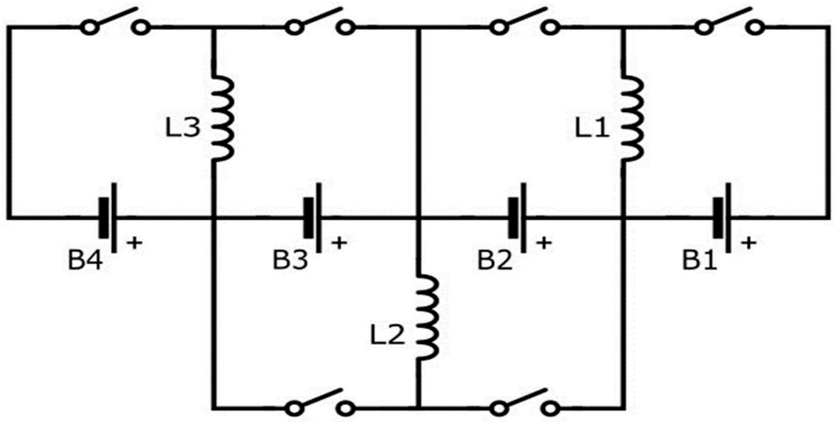


**Figure 15.** Buck–Boost converter equalization circuit.

It has the ability to transfer energy to nearby cells by turning the switch on and off. The Buck–Boost equalization circuit has attracted the attention of many scholars because of its simple structure and fast equalization speed. However, when it is applied to circuits with a large number of batteries, the equalization speed is affected. A new equalization circuit structure based on symmetric power converters was proposed in Reference [75], which decreases the number of inductors and reduces the cost of the circuit. It is shown in Figure 16. B1, B2, B3 and B4 represent battery cells, and L1 and L2 represent inductors in the figure. In Reference [76], according to the Buck–Boost hierarchical circuit, an equalization strategy was suggested, which can achieve simultaneous balance between groups and within groups. The number of transformer windings is almost halved compared with the typical strategy, thus achieving a more compact size and a lower cost. The proposed equalization circuit can achieve multi-unit equalization under severe unbalanced conditions and accelerate the speed of equalization. In Reference [77], both voltage and charge state were taken as equalization variables, and an improved Buck–Boost equalization circuit was designed to form a cyclic energy loop, which achieves modularization and improves equalization speed. To deal with the issue of inconsistent changes in the battery pack's state of charge, Reference [78] proposed a method of equalization integrating the Buck–Boost converter and the reconfigurable topology. The inner layer uses the reconfigurable topology to balance the same group of batteries, and the outer layer connects the battery pack through the Buck–Boost converter to balance the energy. It ensures the stability of the equalization structure while increasing equalization efficiency and cutting costs.

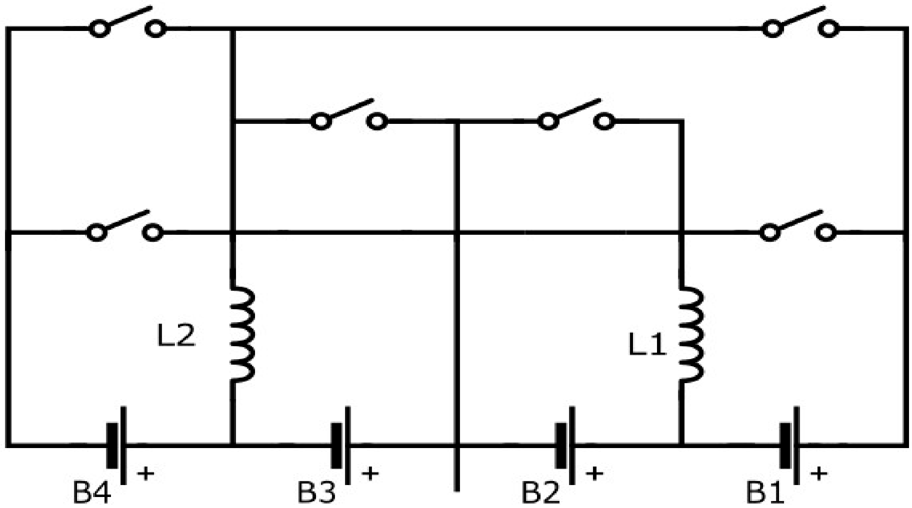


**Figure 16.** Symmetric power converter equalization circuit.

2. Boost converter equalization circuit

The Boost circuit is a DC/DC converter structure that boosts the input to output voltage through at least a buffer element and two semiconductors. The structure is shown in Figure 17. B1, B2, B3 and B4 represent battery cells, L1, L2, L3 and L4 represent inductors, and D1, D2, D3 and D4 represent the diodes in the figure.

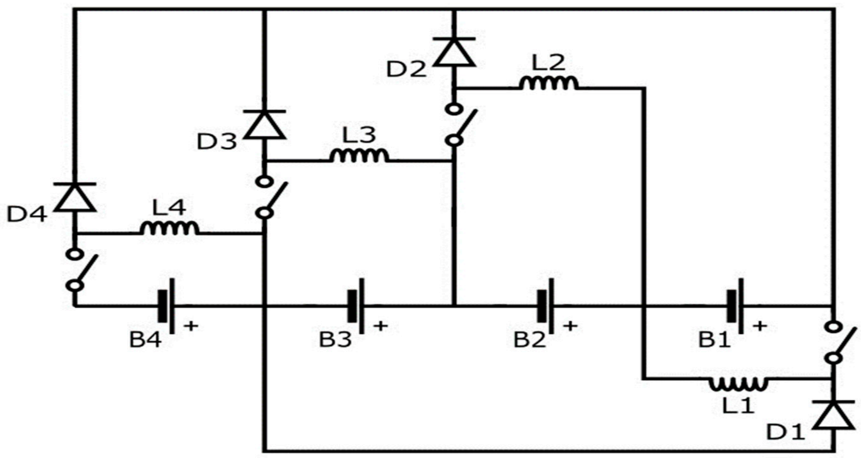


**Figure 17.** Boost converter equalization circuit.

In Reference [79], to deal with a high output voltage, a set of boost modules were linked in series. And, the module's cells discharged cooperatively to cope with the required load conditions. In Reference [80], a kind of new non-isolated boost converter was proposed. This structure adds an additional inductance to the traditional three-level boost converter, which can lessen the switch's voltage stress. Compared with some traditional converters, the suggested converter can lower the components' energy loss by reducing the switching current. It also improves the equalization efficiency.

3. Cuk converter equalization circuit

An effective equalizing circuit is the Cuk converter circuit [81], and its structure is shown in Figure 18. B1, B2, B3 and B4 represent the battery cells, L1, L2, L3, L4, L5 and L6 represent inductors, and C1, C2 and C3 represent capacitors in the figure.

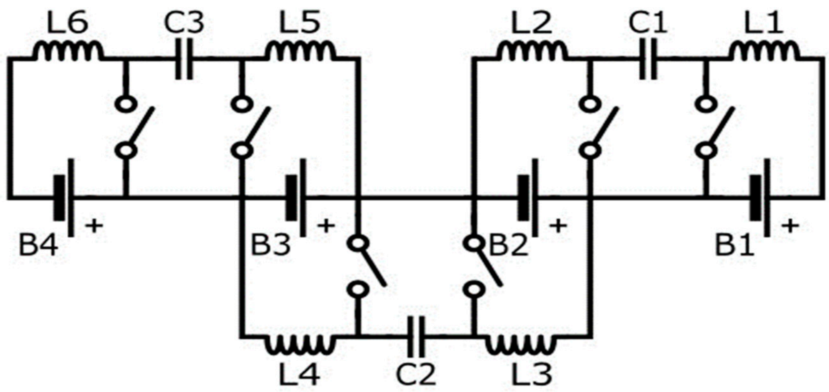


**Figure 18.** Cuk converter equalization circuit.

It is analogous to the Buck–Boost circuit, which has different voltage outputs. The current in the circuit is smoother due to the use of inductors. Similar to the switching capacitor, the circuit's energy can only be moved among cells that are nearby. Therefore, the energy must pass through the intermediate cells when there is a large distance between the two cells, and the equalization efficiency is reduced. The equalization circuit using coupled inductors proposed in [82] solves this problem. The circuit replaces the uncoupled inductors in the traditional Cuk equalization circuit with coupled inductors. Even if there are a lot of cells, the equalization time is greatly shortened. The circuit does not require a complex equalization strategy as well. However, the Cuk converter's voltage and current regulation is more complicated because of the numerous inductors and capacitors. Thus, Reference [83] proposed a new type of Cuk equalization circuit that reduces the quantity of switches needed by the circuit from $2n - 1$ to $n$. It is shown in Figure 19. B1, B2, B3 and B4 represent battery cells, L1, L2 and L3 represent inductors and, and C1 and C2 represent the capacitors in the figure. The loss in the circuit is reduced, and the number of components is also reduced. A topology structure combining a Cuk converter and a double-layer switch is proposed in Reference [84], and the energy transfer between any cell can be achieved through the switch in the circuit, reducing the complexity of the energy transmission path, and the speed also becomes faster than before.

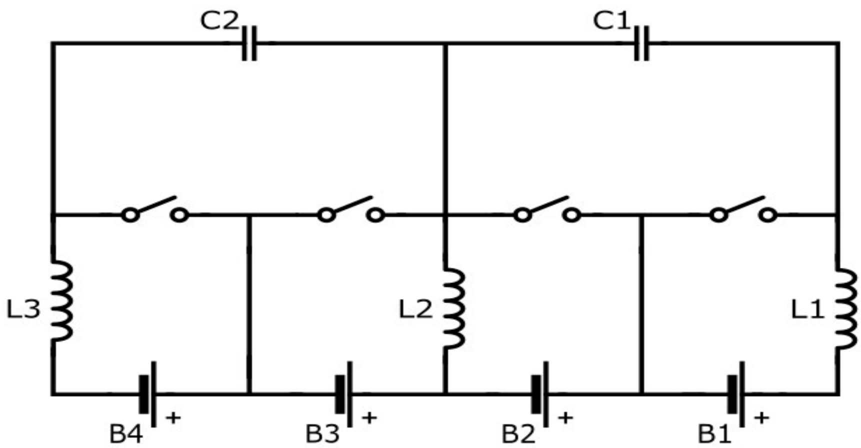


**Figure 19.** A new Cuk converter equalization circuit.

## 3. Discussion

There are many kinds of active equalization topology circuits. Every equalization circuit has benefits as well as drawbacks of its own. According to the actual situation, an appropriate equalization circuit should be selected to achieve the best equalization effect.

The capacitor-based equalization circuit has minimal energy loss, but the reliability and equalization speed cannot be guaranteed. The single-switched-capacitor circuit uses a large number of switches. The same is true of multiple-switched-capacitor circuits. Compared with the multiple-switched-capacitor circuit, the single-switched-capacitor circuit has a lower cost and a smaller volume. The inductor-based equalization circuit consumes less energy like the capacitor-based equalization circuit. In the single-switched-inductor circuit, the stress in the current is very small. When the energy flows in both directions, energy loss is minimal. The speed of the equalization circuit based on a transformer is often faster than that of circuits based on capacitors or inductors. Among them, the single-core multi-winding transformer is simple to control, but the scalability of the circuit is poor. The circuit structure must be modified when the number of cells in the circuit changes. The multi-core multi-winding transformer has good scalability. When the quantity of cells grows or shrinks in the circuit, it is not necessary to change the structure of the transformer, but only to increase or decrease the number of transformers accordingly. The converter-based equalization circuit has low loss and a fast equalization speed. However, its employment also comes with the drawbacks of a high cost and being difficult to control. This circuit can be chosen if the budget allows for such a selection.

As shown in Table 3, this review compares the various active equalization circuits mentioned from the aspects of equalization speed, equalization efficiency, volume, cost, and control difficulty (A indicates that this aspect is optimal, followed by $A^-$, B, and finally $B^-$). The advantages and disadvantages of each equalization structure coexist. When using an equalization circuit, we should choose its advantages and avoid its disadvantages, so as to make appropriate decisions in practical application. If we want a small size and simple control of the equalization circuit, equalization circuits based on capacitors and based on inductors are good choices. When cost is limited and a relatively fast equalization speed is desired, an equalization circuit based on an inductor can be selected. In the case of sufficient cost, if we want a high equalization speed, an equalization circuit based on a transformer or an equalization circuit based on a converter can be selected. When high equalization control is desired, we can choose various equalization circuits based on converters to make the equalization speed faster and the equalization efficiency higher. In general, the faster the equalization speed, the higher the cost of the equalization circuit, so we have to balance performance with cost.

**Table 3.** Comparison of various active equalization circuits.

| Type of Equalizing Circuit | Speed | Efficiency | Volume | Cost | Control Difficulty |
|---|---|---|---|---|---|
| Single-switched-capacitor equalization circuit | B | A | A | A | $A^-$ |
| Multiple-switched-capacitor equalization circuit | $B^-$ | $A^-$ | $A^-$ | A- | A |
| Double-layer switched capacitor circuit | $B^-$ | $A^-$ | $A^-$ | A- | $A^-$ |
| Single-switched-inductor equalization circuit | $A^-$ | $A^-$ | A | A | $A^-$ |
| Multiple-switched-inductor equalization circuit | B | B | A- | A- | A |
| Single-winding transformer equalization circuit | B | B | B | B | B |
| Single-core multi-winding transformer equalization circuit | $A^-$ | $A^-$ | $B^-$ | $B^-$ | $A^-$ |
| Multi-core multi-winding transformer equalization circuit | $A^-$ | B | $B^-$ | $B^-$ | B |
| Buck–Boost converter equalization circuit | A | A | B | B | $B^-$ |
| Buck converter equalization circuit | A | A | B | B | $B^-$ |
| Boost converter equalization circuit | A | A | B | B | $B^-$ |
| Cuk converter equalization circuit | A | A | B | B | $B^-$ |

During use, when the capacity of the power battery reaches 70–80% of the new capacity, its first life is over [85]. As the number of battery-powered cars increases, so will the number of power batteries. If the remaining capacity of the power battery is not used again, it results in a large amount of energy loss. Unlike first-life batteries, second-life batteries are characterized by a large variability in battery capacity and gradually increases as the battery ages. However, the dynamic equalization technique [86] can be used to solve this difficulty. It uses an active equalization system to achieve equalization between second-life cells, for example, a switched capacitor equalization circuit, a Buck–Boost equalization circuit, and the Bilevel Equalization circuit [87]. However, the purposes of dynamic equalization and active equalization are different. Active equalization balances the power in the batteries at specific times. Dynamic equalization keeps the state of the charge of each battery in the other batteries as much as possible during the charge/discharge stage [88]. Therefore, dynamic equalization requires a large current active balance system to maintain the balance of all batteries. This also means that the equalization system becomes more complex. Active equalization technology should be innovated in this aspect. By changing the structure of the equalization topology and the selection of equalization variables, dynamic equalization technologies can improve the available capacity of a second-life battery as much as possible.

## 4. Conclusions and Prospect

There are many factors limiting the development of electric vehicles, including the safety, capacity, and life of battery packs. Various factors cause the cells in the battery pack to produce inconsistencies. Therefore, the pack must be equalized. If there is no balance among the batteries in the pack or the balance effect is very poor, it will reduce the battery pack's service life and safety. More seriously, the battery pack can explode because of uneven power. Battery equalization can effectively decrease battery inconsistencies and improve a battery pack's lifespan. Therefore, the research on battery equalization for electric vehicles has recently gained popularity as an issue. Many scholars have made great contributions to battery equalization, both in terms of equalization strategy and equalization topology. In this paper, active battery equalization circuits were reviewed in detail. They were separated into equalization circuits based on capacitors, inductors, transformers, and converters depending on the various energy storage components. The characteristics of various equalization circuits and the contributions of relevant researchers were summarized. Then, various active equalization circuits were clearly compared in the form of a table. And, the dynamic equalization of a second-life battery and its difference from active equalization were introduced. Although the active balancing topology has a faster balancing speed and a higher balancing efficiency, it often has more complicated control modes and a higher cost. An appropriate equalization circuit should be selected according to the actual situation to achieve an optimal equalization effect.

Although in recent years, much research has been conducted on battery equalization, many strategies are still in the experimental stage [89]. There are several challenges to overcome before these technologies can be widely implemented in practical application. For example, converter-based topologies demonstrate high efficiency and fast equalization speeds, but their complex structure leads to increased costs, making large-scale deployment less feasible. Finding ways to minimize costs without compromising efficiency is thus crucial. Potential future research directions to enhance battery equalization efficiency include the following:

- Optimizing Topologies: Integrating and optimizing topologies to enhance efficiency and minimize complexity.
- Exploring Additional Variables: Exploring additional equalization variables to improve the effectiveness of the technology.
- Developing Advanced Control Algorithms: Developing advanced control algorithms for dynamic adjustment based on operating conditions.
- Extensive Testing and Collaboration: Conducting extensive testing across diverse applications to ensure robustness and fostering collaboration between academia, industry, and government for accelerated development and adoption.

By focusing on these research areas, it is anticipated that the efficiency and practicality of battery equalization systems will be significantly improved, ultimately facilitating the widespread deployment of advanced energy storage solutions.

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supervision, L.Z.; funding acquisition, L.Z. All authors have read and agreed to the published version of the manuscript.

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