Equalization circuit topologies of lithium battery strings: a brief review

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Abstract. Lithium batteries are widely applied in new energy vehicles and related energy storage industries due to their superior performance. The application of an equalization circuit can effectively reduce the inconsistency of the energy of the battery pack, thereby extending the service life of the battery pack. By reviewing the mainstream balanced circuit topology, this paper proposed the comments on the ideal balanced circuit structure in the future, which is expected to serve the construction of large-scale energy storage system in the energy Internet.

1. Introduction
The operating parameters such as the output energy and specific power of the battery pack cannot reach the performance of the single battery, and the use limit is far different from the single battery, which results in increased system operation and maintenance costs, reduced safety and economy, and limited lithium. The promotion and application of batteries hinders the vigorous development of related industries. Implement external circuits to the battery pack to adopt status monitoring and effective management to improve the chargeable and dischargeable capacity and enhance the energy utilization of the battery to avoid the battery power exceeding the threshold, thereby enhancing durability and reducing operation and maintenance costs.

The battery management system has always been regarded as the core part of electric vehicle management [1]. There are many differences between power batteries mounted on electric vehicles and ordinary consumer lithium-ion batteries. Their structure is more complicated, the number of monomers is greater, and the demand for safety and reliability is stricter. The above-mentioned reasons lead to the importance of the balanced circuit, which has become the main competitive advantage of electric vehicles. Through the research of this subject, the design and optimization of the balanced circuit of the power battery pack can reduce the loss, extend the battery life and the mileage of the electric vehicle, solve the technical dilemma faced by the development of electric vehicles, and help the booming development of the electric vehicle industry.

2. Current states and progress of research
The way of lithium battery pack energy balance is mainly achieved through chemical and physical principles. The physical balancing strategy of the power battery pack is divided into passive balancing and active balancing according to whether controlled components are used. Passive equalization refers to the conversion of the energy of overcharged batteries into heat or other forms of energy by means of energy-consuming components such as resistors, thereby reducing the energy difference of individual
cells in the battery pack and ultimately achieving the consistency of the overall energy. The passive equalization technology that is usually used to consume excess energy in parallel with a resistor or voltage regulator next to the battery. Although the circuit structure is simple, there are problems such as heat generation and a lot of energy waste. It has been gradually eliminated and active equalization refers to the use of transformers and energy storage devices such as capacitors absorbing the energy in the overcharged battery and then release it to the undercharged battery to realize the secondary distribution of energy between the batteries, thereby reducing the difference between the individual cells of the battery pack. In recent years, scholars at home and abroad have conducted extensive research on the energy balance of lithium battery packs using DC converters.

2.1. Network balance of energy storage components
The use of inductors and capacitors to form energy storage networks for energy transfer is the first lossless equalization applied after dissipative equalization. Such schemes generally have the advantages of simple structure and convenient control, and are widely adopted in small-scale environments. However, in the process of switching capacitors or inductances, the transient current is too large, resulting in the effects of arcs and electromagnetic interference, which increases the balance loss, and is not suitable for large-scale energy storage system balance. The mainstream energy storage element network equilibrium topology is shown in Figure 1.

![Energy storage element network equilibrium topology](image)

**Figure 1.** Energy storage element network equilibrium topology: (a) Capacitive; (b) Inductive.

The K. W. E. Cheng group [2, 3] of the Hong Kong Polytechnic University chose high-speed switched capacitor network equalization technology to achieve the energy balance of adjacent cells in a series battery with the help of capacitor banks. At the same time, related research has been carried out in terms of reducing energy loss or optimizing system performance, and an energy optimization method in a battery / supercapacitor hybrid energy system has been proposed to realize the working process of reliable and coordinated power supply of the two, with high adaptability and scalability. It has the characteristics of simple control and control, but when the energy difference between energy storage monomers decreases, the time consumption of this method will be prolonged significantly.

A. Baughman et al. [4] used the flying capacitor equalization technology to directly equalize the highest and lowest energy storage cells. This method can be arbitrarily expanded according to the number of monomers, but the energy needs to be transferred in sequence, resulting in a large number of switches, a complicated circuit structure, and a large starting current of the device, which is likely to produce arc or electromagnetic interference, and the voltage drop at the switch will also be large Interference equalization process.
Prof. Shang Yunlong of Shandong University proposed a switch-coupling capacitor balancing topology [5, 6], which can achieve the balancing of any cell to any cell of the battery string without the need for a battery monitoring circuit. The proposed equalizer shares a single converter to balance between the unit and the module, thereby achieving a smaller size and lower cost. However, the presence of a large surge current will cause overheating of the components and damage to the electrodynamics.

2.2. Multi-output winding transformer equalization

This kind of equalization circuit uses a multi-winding transformer in the middle. When the switch is on, the excess energy is absorbed by the primary winding of the transformer. When the switch is off, the energy is released to the undercharged battery through the secondary winding. According to the current level of transformer manufacturing, for example, the relevant parasitic parameters of the transformer, especially the presence of leakage inductance, will lead to differences in the energy of individual cells in the battery pack. The mainstream multi-output winding transformer equilibrium topology is shown in Figure 2.

![Balanced topology of energy storage element network](image)

**Figure 2.** Balanced topology of energy storage element network: (a) Single-tube flyback converter; (b) Multi-tube flyback converter.

K.-M. Lee uses several transformer topologies to achieve energy transmission goals [7]. The energy of the overcharged battery is stored by the primary winding, and then released from the secondary winding to the weak unit through the switch module. This equalizer has flexible control functions, but its design is more complicated and expensive, and it is also limited by device saturation. Teacher Xu Aiguo ignored the role of the switch module and assigned the secondary winding to each equalizer [8]; C.-H. Kim split the primary winding into two parts to make it work in concert [9]. S.H Park has a deeper distribution on the primary and secondary windings [10]; X. Wang uses inductive taps as the core structure of the autotransformer [11]. A. M. Imtiaz proposed the topology of the time-sharing flyback converter [12], in which any single battery cell in the battery pack can be balanced. Each unit shares an equalization module in the control gap of the low-power microcontroller and applies the transformer to the topology, which limits the volume and weight of the converter to some extent. C.-S. Lim proposed a new switching circuit without voltage estimation [13], which uses a single charge equalizer based on a multi-winding transformer, the converted energy is transferred by the magnetic circuit of the multi-winding transformer, which inevitably leads to a large number of
Magnetic loss. The counterattack topology is widely used in isolated conversion circuits. The Kutkut NH team studied the use of transformer equalization. The disadvantage is that the secondary winding cannot be accurately matched. The voltage difference formed by the internal leakage inductance of the transformer is difficult to compensate and cancel [14, 15].

2.3. Equalization of buck-boost converter
Since the lithium battery can be approximated as a DC source, a DC conversion circuit can be selected to achieve energy transfer, thereby reducing the energy difference of the single battery. Commonly used topological forms are Buck/Boost and Cuk circuits. Nishijima proposed an inductor equalization circuit [16], whose topology is similar to a switched capacitor circuit, and they replaced the capacitor with an inductor. This design increases the actual capacity of the equalizer and achieves fast equalization. However, because every two adjacent equalizers share a switch, the coupling effect of the switch makes the mathematical description of the equalizer complicated. Zhao Juan of Beijing Jiaotong University managed to control the three strings of batteries [17], but the design of the magnetic circuit parameters was more complicated due to the coupling effect. Yuan-Shung Lee added a resonant loop to the equalizer to reduce switching losses [18]. The mainstream buck-boost converter adopted for batteries equalization is shown in Figure 3.

![Figure 3. Buck-boost converter circuit: (a) Buck / Boost converter circuit; (b) Cuk converter circuit.](image)

In addition, Cassani analyzed the feasibility of such circuits from a control perspective and concluded that with the number of units, the number and complexity of controllers increased exponentially [19]. He also reduced the workload of each controller by dividing the batteries into several groups [20], and proposed a compromise solution. The potential performance of these inductive equalizers is limited by ineffective control, and their application in fast equalization is limited to small battery packs. Guo Xiangwei of South China University of Technology has improved the traditional topology, and designed a lossless equalization circuit with energy transfer in both directions [21]. Its control method is simple, the equalization speed is faster, and the system has higher equalization current and relatively excellent Balanced performance.

2.4. Improve the buck-boost circuit balance
The traditional one-to-one equalization topology is usually implemented with an improved buck-boost circuit to realize one-to-many, any-to-any, and many-to-many equalization. In the balancing process, the battery with the highest energy transfers energy to multiple energy storage units connected in
series below. The specific situation of multiple charged cells is hard to be considered, and the balancing speed is relatively low. The improved topologies of the buck-boost circuit are shown in Figure 4 and Figure 5 respectively.

![Figure 4. Buck/Boost converter with virtual battery.](image)

![Figure 5. Buck/Boost bidirectional converter circuit.](image)

C. Zou proposed a new algorithm that uses a new model-based method to manage the battery charging process [22]. C. Zhang developed a polarization-based charging time and temperature rise optimization strategy for lithium-ion batteries [23]. An enhanced thermal behavior model is introduced to improve the calculation accuracy at high charging currents, in which the relationship between polarization voltage and charging current is solved. In [24], the researchers developed a new 16-phase interleaved bidirectional DC/DC converter with a smaller input/output filter, faster dynamic response and lower equipment than traditional designs. A new soft-switching topology for discontinuous current mode operation is proposed, which implements zero-voltage switching or zero-current switching during the transition process for future research.

Recently, domestic and foreign scholars have made unremitting efforts to design more efficient battery balancing systems. For example, in [25], a controller based on fuzzy logic was developed to reduce the equalization time of the series battery system. The controller has been tested for a three-cell series system. In addition, Literature [26] proposed a new battery equalizer configuration, and analyzed its performance and cost, and tested the equalizer using computer simulation and physical experiments on a 5-cell system. In Reference [27], a layer-based cell balancing system is introduced. Using MATLAB simulation and a circuit experiment with four batteries in series, the efficiency of the layer structure is compared with the traditional series-based equalization structure. In the traditional equalization-based equalization structure, all equalizers and batteries are connected in series. The results show that the layer structure can effectively shorten the system equilibrium time.

3. Conclusions and future works
This research summarizes the research background of power management technology, mainly introduces the application status and development prospects of lithium-ion battery packs in the field of new energy vehicles and energy Internet, and then describes the main research content of this article. The importance of building the ubiquitous power Internet of Things. Then, by summarizing and analysing the research status at home and abroad, the existing mainstream equalization circuit topology and its control strategy are compared to determine the research direction of battery power management and control methods.

It is not only necessary to design and adopt strategies such as soft switching and reducing the quality of inductance, and develop a small and low-loss, safe and reliable balanced circuit topology. The current research on the balancing of series-connected battery packs can also be improved in terms of circuit design, making breakthroughs in features such as high degree of freedom, high flexibility,
easy expansion, and large-scale application. It should deal with and deal with the balancing limitations at high currents, while avoiding the electromagnetic interference of the power transmission part and the high-frequency signal outside the circuit cause a malfunction.

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