Research progress of energy equalization topology of power lithium battery pack

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Abstract. At present, with the vigorous development of electric vehicle industry, power battery, as an important power source of electric vehicle, has attracted more and more attention of researchers. Among many kinds of power batteries, lithium-ion battery has been widely studied by many experts and scholars because of its clean, pollution-free and other advantages. As an important part of battery management, battery energy equalization technology makes the energy in the battery pack flow between single batteries by building an equalization circuit, which provides a strong guarantee for the efficient output and stable operation of lithium-ion batteries. This paper summarizes the current equilibrium topology of lithium-ion battery pack by summarizing and combing various types of existing equilibrium structures. According to the development process of equilibrium technology, this paper introduces the working principles, advantages and disadvantages of passive equalization, active equalization and active passive hybrid equalization structure, and summarizes the design idea of current equilibrium circuit by systematically summarizing the characteristics of the development of equilibrium circuit structure in recent years, According to the latest research progress, grasp the future development direction. Finally, according to the current balanced technology development, this paper puts forward personal views and prospects for the future balanced technology development.

1. Introduction

In recent years, with the society vigorously promoting green travel, electric vehicles have gradually entered the public's vision. Compared with traditional fuel vehicles, electric vehicles are sought after by the public for their clean, pollution-free, environment-friendly and other characteristics. Nowadays, the electric vehicle industry is developing rapidly and has the potential to replace fuel vehicles as the mainstream of future vehicle development. As an important power source of electric vehicles, lithium-ion batteries have been widely studied by many scholars because of their advantages such as high energy density, long service life and no memory effect[1] . Usually, power battery packs are connected by multiple battery cells in series and parallel, so as to achieve the performance indicators such as output voltage and battery capacity required by electric vehicles[2] . However, considering the differences in the real environment and production process, there are differences in the performance of individual cells such as internal resistance and self discharge rate, and the actual performance of individual cells can not be consistent. With the accumulation of the operation time of the battery pack, the performance differences of battery cells will be gradually enlarged, leading to the imbalance of energy among cells [3] . Based on the "barrel effect", the capacity of the battery pack will be restricted by the low-power cells, which will easily lead to excessive charging and discharging of the battery pack, cause irreversible damage to the battery cells, and affect the overall performance and service life of the battery pack[4] . The equalization technology can solve the problem of inconsistent energy of individual batteries well. Whether it is to consume the power of cells through energy consuming elements or to transfer energy between cells through energy storage elements, the energy balance of battery packs can be achieved and the actual effect is stable and reliable. The in-depth research of battery equalization technology is of great value to the development of electric vehicles in the future.

2. Introduction to equalization method

The purpose of the energy balance technology[5] is to reduce the energy difference between the individual cells in the battery pack, maintain the battery power at a relatively balanced level, weaken the damage caused by

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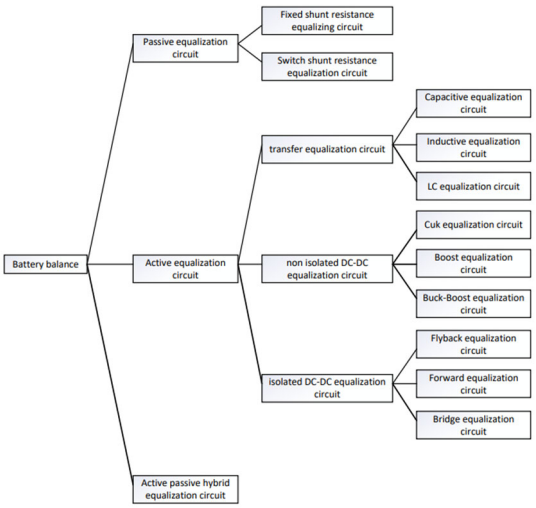

Figure 1. Classification of basic battery balancing topology

energy imbalance to the output performance of the battery pack, and extend the service life. According to the different treatment methods of energy in the equalization process, energy equalization can be divided into passive equalization and active equalization[6] . With the continuous development of equalization technology, the category of active passive hybrid equalization has emerged in recent years. The active passive hybrid equalization circuit combines the advantages of active equalization and passive equalization, and can further improve the energy equalization effect of the battery pack. The specific classification of these three types of equilibrium methods is shown in Fig.1.

3. Passive equalization circuit

The passive equalization method uses the method of parallel resistance branches at both ends of each cell to consume the energy of the cell, and releases the electric energy to the outside in the form of heat, so as to achieve the goal of consistent energy of each cell. Passive equalization circuits are simple in structure, stable, reliable and expandable, but resistance heating will shorten the service life of batteries. Nowadays, they are mostly used in low-power equalization circuits[7,8].

The reason why passive equalization can achieve uniform battery power is that the current flowing through the parallel resistance branch is in direct proportion to the terminal voltage of each cell, and the terminal voltage of the cells with different energy reserves is different, which makes the energy loss of the cells with high power consumption fast and the energy loss of the cells with low power consumption slow, so as to finally achieve uniform power within the battery pack[9] .

At present, there are two main passive equalization methods, namely, fixed shunt resistance equalization and switched shunt resistance equalization[10] . The fixed shunt resistance structure realizes power balance by directly connecting resistors in parallel at both ends of each cell. The advantages of this structure are simple structure, low cost, good equalization effect, stability and reliability; On the other hand, this structure will cause serious and uncontrollable energy loss. Excess energy will be lost in the form of heat, resulting in energy waste. In addition, the heat generated by the resistance will accelerate the aging of the battery pack, affect the output performance, and have higher requirements for the thermal management system. Compared with the fixed shunt resistor structure, the switch shunt resistor structure aims to achieve balanced power loss control to a certain extent. By adding a switch to the shunt resistor branch and controlling the on-off of the switch to achieve energy balance, the balanced structure is more flexible and the energy loss is reduced. At the same time, taking into account the advantages of simple structure, economy and reliability, it is still widely used in practical industrial applications. However, the problem of energy loss in the form of thermal energy still exists, which affects the service life of the battery pack[10] , and the equalization speed is slow. This equalization method is not suitable for the balanced use of high-power battery packs[11] .

4. Active equalization circuit

The active equalization method is to transfer energy from high-power cells to low-power cells by using energy storage elements such as capacitors and inductors. Compared with passive equalization, active equalization greatly reduces the power loss, greatly improves the energy utilization rate of the battery pack and has low heat output, reducing the pressure of the thermal management system[12] . Active equalization technology is a hot research direction of equalization technology at present.

Active equalization structure can be divided into transfer equalization structure[13] and DC-DC equalization structure according to whether DC-DC conversion circuit is used in equalization circuit. On this basis, DC-DC equalization structure can be further divided into non isolated DC-DC equalization structure[14] and isolated DC-DC equalization structure[15] according to whether electrical isolation is performed in equalization circuit.

4.1 transfer equalization structure

Transfer equalization circuit refers to the energy equalization circuit that uses energy storage elements as the medium of intermediate energy transfer. According to different energy storage components, it can be divided into capacitive equalization circuit, inductive equalization circuit and LC equalization circuit[16] . Capacitive equalization circuit[17,18] realizes the transfer of electric energy through capacitors. Since capacitive equalization realizes the transmission of electric energy based on the voltage difference between cells, the size of the voltage difference between cells will greatly affect the equalization rate of cells. As the equalization time continues, the electric voltage difference will gradually decrease, the energy transfer efficiency will decrease, and the equalization effect will become worse. Inductive equalization[19,20] uses the inductor as an energy transfer device, making the control of the equalization circuit more convenient and accurate, and reducing the loss in the energy transfer process. LC circuit equalization

method[21,22] solves the problem of small voltage difference in capacitor equalization circuit by introducing LC oscillation circuit, but the switching frequency is high and the circuit control is complex.

In order to solve the problem that the voltage of each single battery in series is inconsistent in practical application, literature[23] proposed a voltage equalization circuit based on LC circuit and bidirectional switching unit. The circuit is composed of a series cell unit, a bidirectional switch unit and an LC circuit. The cell with the highest voltage is transferred to the LC circuit, and then transferred from the LC circuit to the cell with the lowest voltage. The equalization path is independent of the cell location, which effectively shortens the energy transmission path and improves the energy utilization rate. The characteristics of easy expansion and small size of the circuit further enhance its practicability.

Literature[24] proposed a battery strings equalizer circuit based on switching capacitance. In the circuit design, considering the small size and easy control of the capacitor, the capacitor is used as the carrier of energy transfer. Through multi-channel energy transmission, the energy in the battery pack flows from the highest voltage battery cell to the lowest voltage battery cell, which not only improves the equalization speed, but also shortens the energy transmission path to achieve simultaneous equalization of multiple battery cells. However, the disadvantage is that with the increase of the number of cells, considerable switching loss will be brought, and it is impossible to ensure that the equalization effect is always at a high level.

Literature[25] proposed series-parallel battery pack balancing circuit with single inductor. The series battery pack is connected in parallel with a single inductance element, and the energy flow is controlled by a control element to achieve energy storage and transfer in the inductor, so as to achieve simultaneous equalization of each battery cell. This equalization circuit structure has the characteristics of simple structure, small size, easy expansion, etc. The equalization speed is improved compared with the conventional single inductor structure, but it is still restricted by the single battery series parallel structure.

4.2 Non isolated DC-DC equalization structure

The equalization circuit of non isolated DC-DC converter relies on DC-DC circuit to realize energy equalization. According to the structure classification, it can be divided into: Cuk structure, Boost structure, Buck Boost structure, etc. The balancing method is more flexible, easy to topology, high integration, and excellent balancing performance, which is an important research direction[26] .

In order to solve the problem of unbalanced power distribution among cells in the battery pack, literature[27] proposed a charge discharge equalization circuit for parallel battery packs. During the charging process, the cell with the voltage up to the cut-off voltage is removed from the charging circuit; During discharge, Cuk circuit is used to compensate the unit with the lowest power, so as to balance the power distribution in the battery pack. This scheme realizes the rapid equalization of the battery cell with remarkable equalization effect, effectively maintains the service performance of the battery pack, maintains the charge and discharge capacity of the battery pack, and extends the service life of the battery pack.

Reference[28] proposed a reconfigurable Buck Boost charging equalization structure to improve the battery equalization speed and reduce the energy loss during the equalization process. This structure combines the characteristics of the Buck Boost circuit, which can realize the power balance between non adjacent battery cells, and the reconfigurable circuit, which has short equalization time and low energy loss, making the performance of this reconfigurable Buck Boost circuit significantly reduce the equalization time and improve the energy transfer efficiency compared with the conventional Buck Boost circuit.

To solve the problem of unbalanced energy distribution of large battery packs, literature[29] proposed an energy balanced structure with multiple structures and multiple states for a series battery system. The cell in the battery pack is divided into several units to realize the internal independent equalization of each unit. The equalization process is divided into multiple states. The Buck is constructed by controlling the on-off of the switch, and the Boost circuit completes the energy transfer between each energy unit and the external variable voltage source. In the static state, each unit is balanced simultaneously, which improves the equalization speed of the battery pack. This multiple multi state equalization structure solves the problems of slow equalization speed and low equalization efficiency of large battery packs, and greatly improves the equalization speed and service life.

4.3 Isolated DC-DC equalization structure

The isolated DC-DC equalization structure is mainly based on the isolated DC-DC conversion circuit structure. The energy transfer is realized through the transformer structure, and the input and output terminals are electrically isolated. Common isolated DC-DC equalization circuits are mainly divided into flyback circuit, forward circuit and bridge circuit[27] . Isolated DC-DC equalization circuit is widely concerned because of its fast equalization speed, safety and reliability, and high stability[30] . At present, flyback structure is a kind of equalization structure that is widely used in various isolated DC-DC equalization structures.

Reference[31] proposed a lithium battery pack equalization circuit based on flyback converter. This circuit design connects the corresponding battery cell with other battery cells through the main and secondary coils of the transformer, and the energy flows through the primary and secondary side coils to achieve the purpose of equalization. The flyback transformer itself has the characteristics of electrical isolation. Each equalization module is relatively independent, and each module can be equalized at the same time. Compared with the traditional equalization circuit, the equalization speed and efficiency of this circuit are effectively improved.

In order to solve the problem of single equalization mode, literature[32] proposed a multi state equalization structure

based on three winding transformer, which designed multiple equalization circuits integrated in the same circuit for the possible energy imbalance of the battery pack. By controlling the on-off of the switch, the battery pack equalization mode is adjusted in real time, and the battery pack is always in the best energy balance state, so as to achieve the optimization of the output performance of the battery pack. This design scheme has short equalization path and can realize bidirectional transfer of energy between objects. The equalization effect and fast equalization speed are improved, further improving the output performance and service life of the battery pack.

5. Active passive hybrid equalization structure

Active passive hybrid equalization structure is a new type of energy equalization structure which combines the advantages of active equalization and passive equalization. The active passive hybrid equalization structure combines the advantages of passive equalization, such as simple structure, strong scalability, stability and reliability, and the advantages of active equalization, such as high equalization rate and low energy loss. In the circuit design process, balance the equalization rate and energy utilization rate to further optimize the energy equalization effect of the circuit and improve the equalization efficiency of the actual circuit.

In order to solve the problem of slow equalization speed and low equalization efficiency of the battery pack, literature[33] proposed an active passive hybrid equalization circuit. The circuit is divided into resistance module and LC oscillation circuit module. The LC oscillation circuit is used to ensure the equalization speed of the battery, and the resistance passive equalization circuit is used to delay the capacity growth rate at the initial and final stages of charging and discharging, so as to quickly estimate the battery charging and discharging state.

Reference[34] proposed a hybrid equalization circuit, which combines the switch shunt resistor structure and the isolated DC-DC equalization structure to passively equalize the extremely high power cells, quickly release the excessive power of the cells. When the power dispersion of each cell is moderate, the active equalization structure transfers the power from the whole to the low power cells to achieve energy equalization. These two circuit designs give consideration to the equalization efficiency and speed, reduce the requirements of the circuit on the equalization strategy, and maintain the battery performance and service life.

Based on the above introduction to the equalization structure of the battery pack, the advantages and disadvantages of the basic equalization structure are analyzed, as shown in Table 1.

Table 1. Comparison of advantages and disadvantages of basic equalization structure

energy equalization circuit	advantage	disadvantage
Fixed shunt resistor equalization circuit	Simple structure, low cost, good scalability, stability and reliability	Large energy loss, low balancing efficiency and high heat generation are unfavorable to the battery pack
switched shunt resistance equalization circuit	Simple structure, low cost, reduce energy loss	The energy utilization rate is low, and the heat emission is unfavorable to the battery pack
transfer equalization circuit	Simple structure, easy to control, high energy utilization and good scalability	Slow equalizing speed, many control switches
non isolated DC-DC equalization circuit	High equalization efficiency and short energy transmission path	Complex control and large number of control switches
isolated DC-DC equalization circuit	High equalizing speed and efficiency, and bidirectional energy flow	High cost, large circuit volume, not conducive to expansion
Active passive hybrid equalization circuit	High equalizing speed and efficiency	Increased energy loss and calorific value of the circuit

6. Conclusion

At present, the electric vehicle industry is developing rapidly. As the main power source of electric vehicles, lithium-ion power batteries are the focus of current research in terms of capacity expansion and performance optimization. While continuously pursuing the high performance of the battery pack, it is still necessary to comprehensively consider the stability and safety of the battery pack. The battery energy equalization technology can improve the safety and stability of the battery pack to a certain extent, improve the energy utilization rate, reduce the generation of heat, improve the overall battery life, slow down the aging speed, and improve the stability and safety of the battery pack.

Energy equalization technology, as the main means to solve the uneven power distribution of power battery pack, is of great value to the development of China's electric vehicle industry. This paper combs the development

process of power battery energy balance technology at the current stage from two perspectives. First of all, horizontally sort out the existing types of balanced structure and the current latest achievements; Secondly, it introduces the research and design direction of each equilibrium type vertically, summarizes the current research progress, and grasps the future development direction.

With the constant introduction of various equilibrium structures, from passive equilibrium, active equilibrium to active passive hybrid equilibrium, the structure tends to be relatively complex, while the equilibrium effect, rate and energy utilization rate are constantly improving. Compared with the power grid energy storage equalization technology, the requirements of the on-board power battery for the equalization circuit tend to be small in size, high in energy utilization, fast in equalization speed, etc., in order to achieve a longer mileage. The development of equilibrium technology has changed from passive equilibrium, active equilibrium to active passive hybrid equilibrium, from the initial requirement of stability and reliability to the design concept of low loss and high energy utilization, and then to the current equilibrium rate, energy utilization, and refined and simplified structure, which reflects that under the guidance of the market, the transformation of the design concept of equilibrium technology will be the development direction in the future.

In the aspect of balanced circuit function design, in order to make the application scope more extensive, the circuit design tends to multi structure mixed, multi-mode, multi state design ideas. Compared with the single equalization method, the design idea of multi-mode and multi-state is more conducive to broaden the practical application range of the equalization circuit, but the circuit structure is more complex, which is a stage in the development process. However, how to maintain a good energy balance effect while meeting the overall lightweight of the battery pack needs to be considered in the next step.

To sum up, in the current environment of rapid development of electric vehicles, battery energy equalization technology has developed rapidly. At present, the focus of energy equalization technology is how to take into account the needs of battery packs in terms of energy utilization, equalization speed, and structure simplification, so as to further optimize and innovate the energy equalization technology.

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