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Series-connected battery equalization system: A systematic review on variables, topologies, and modular methods

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Summary

Series-connected lithium battery packs are widely adopted in industries such as electrical vehicles and large-scale energy storage systems. It is necessary to configure an equalization system for them to reduce the inconsistency of single cells, to ensure the battery pack cycle capacity. Although many novel active converters have been proposed for equalization, there still lacks systematic analyses on variables, topologies, and modular methods. Therefore, this paper provides a systematic review on the above aspects. Initially, an overall summary is present on current variables for equalization control. Second, the dominant structures are divided into cell-to-cell, cell-to-pack, and pack-to-pack topologies, and their characteristics are pointed out for comparison. And then, the modular methods, including single-layer-based, multi-layer-based, and hybrid integrations are evaluated via graph theory. Some key issues and potential research directions are given, which are expected to offer assistance on the selection of appropriate variables and topologies for equalization systems in the future.

KEYWORDS
battery, equalization, modular methods, topologies, variables

1 | INTRODUCTION

It is undeniable that the interconnection of power grids and the improvement of transmission and storage are the development directions to avoid future power crises. During the extreme cold weather in early 2021, Texas, the only state with independent power grids in the United States, experienced large-scale continuous power outages, causing huge economic losses.[1] Whether serving energy transmission between interconnected power grids or providing continuous power to local power grids in the event of a failure, energy storage systems can improve the robustness of the power system in the face of extreme weather and sudden failures.

The large-scale applications of battery energy storage technology have alleviated the current issues on energy storage and provided the necessary support for the construction of a robust smart grid.[2] This inconsistency of state in the single battery will reduce the output performance of the whole battery pack, and even lead to accidents such as spontaneous combustion and self-explosion.[3,4] The literature analyzes the difference in rate characteristics of single cells and the reason for accelerating the inconsistency.[5,6] Whereas the aging lithium batteries in new energy vehicles can be recycled and reused in other industries such as photovoltaic systems, this technology still encounters many issues and can hardly be commercialized for now.[7] Therefore, the application of power electronics technology such as the balanced circuit system to perform the secondary distribution of energy to each cell in the battery strings, thereby reducing the inconsistent phenomenon caused by the overcharge or overdischarge, is the feasible guarantee of the battery pack cycle life selection.[8]

Nowadays, the mainstream review papers focus on battery state of charge (SOC) estimation or independent analysis and evaluation of the balanced circuit.[9,10] Even though these review papers give certain suggestions for related researches, they can hardly provide comprehensive development suggestions because those determinants are analyzed independently. Besides, there is a good attempt such as Reference 11, in which a comprehensive discussion on the recycling process is provided, whereas the research gap on the systematic analysis of battery equalization still exists. Hence, the motivation is strong and the potential benefits of the systematic review on equalization are large. On the one hand, the variables of battery balancing are considered and suggestions on improvements are given on the results and deficiencies of the corresponding estimation methods; on the other hand, it will conduct a mainstream active balancing topology from the perspective of the object of energy inflow and outflow. The classification is given and the proposal on the ideal balanced sub-module design is clear. On this basis, reviewing and comparing the hierarchical grouping of multi-cell balancing systems, the graph-based analysis method is probably the solution in which most topologies could be taken into a systematic evaluation under normal circumstances. The improvement and actualization of advanced battery equalization technology will provide the cornerstone for large-scale energy storage systems, thus serving the development of energy unions and the energy Internet[12] (Figure 1).

The remainder framework of this paper is organized as follows. In Section 2, some equilibrium variables are presented to make a thorough comparison. Besides, the merits and limitations of each variable are analyzed and discussed. In Section 3, a classification of active converters is presented based on energy flows. Section 4 compares the effects of different layered modeling strategies on the whole system. And then, some key issues and developing trends are provided and analyzed in Section 5. Finally, the overall conclusions and some potential works are summarized in Section 6.

2 | EQUILIBRIUM VARIABLES

The variables of the equilibrium are key issues that affect the performance of the battery strings, which will directly influence the effect of equilibrium and the working time of the system.[13] Appropriate variables can effectively improve the accuracy and time of equalization. Generally speaking, the indicator variables at the end of the balancing process can be divided into state of energy (SOE), state of voltage (SOV), SOC, state of health (SOH), and state of function (SOF).

The equivalent circuit model based on the external characteristics will directly determine the effectiveness of the application of battery balancing variables.[14,15] There

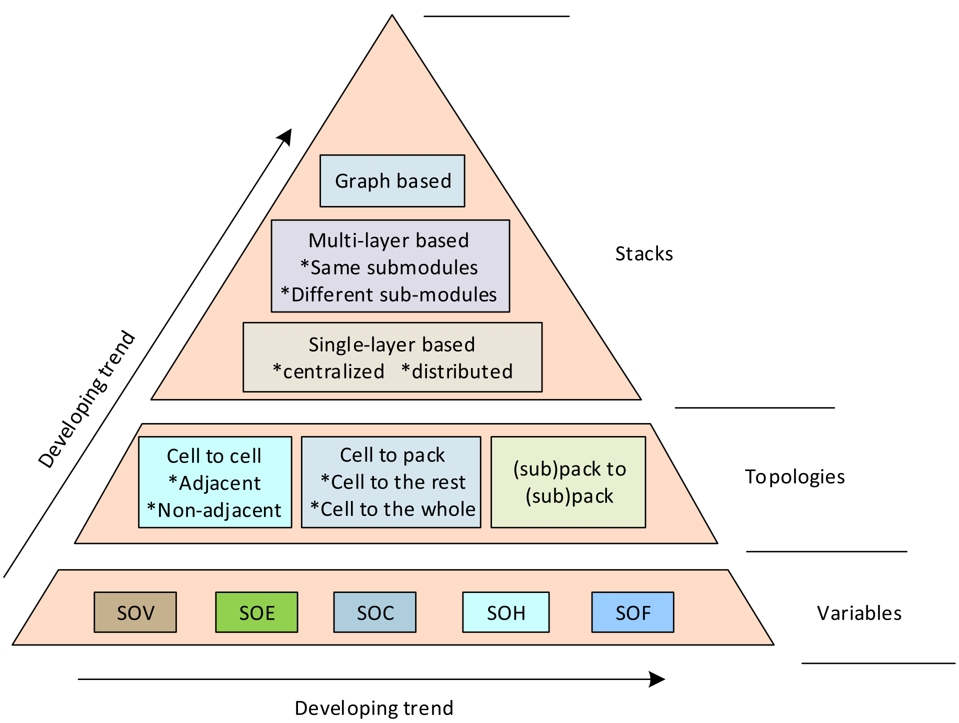

FIGURE 1 The developing trend around battery equalization system [Colour figure can be viewed at wileyonlinelibrary.com]

are four dominant models for batteries that should be introduced before the analysis of the variables. The Rint model can be obtained by approximating the external characteristics of the battery as linear, which is shown in Figure 2A. This model is simple but rough because the characteristics of the battery are non-linear in most cases. Therefore, the RC equivalent model, which is shown in Figure 2B, is proposed to mitigate this issue, which consists of two capacitors and three resistors. The transient effect and polarization effect of the battery during operation are taken into consideration, but it lacks the design of efficiency inconsistency during battery charging and discharging. The Thevenin model and the Partnership for a New Generation of Vehicles (PNGV) model, shown in Figure 2C,D, respectively, are widely adopted in applications since they have the characteristics of high model accuracy and easy parameter identification experiments.

2.1 | SOV equalization

The voltage of the battery could be directly observed and collected, which was initially utilized as an indicator of consistency on the battery. As shown in Figure 3, the initial difference in the voltage of each battery is eliminated, which suggested that the equalization have been achieved during charging, idling, and discharging progress. Due to the determinants of voltage includes the energy, the resistance, the temperature, and so on, the consistent representational terminal voltage not always be the end of the final equalization of the battery pack. Whereas this variable enables simple logic and control on equalization management, which has been widely adopted into applications by researchers.

The voltage of batteries is not only the variable for determining the end of the equalization, but also provides the unequal potential to obtain equalization current.[16] The proposed natural equalization control does not need voltage and current detection equipment. Energy could naturally flow to where it is needed whereas this method adopts the equalizing current generated by the electromotive force at both ends of the bridge arm to adjust the voltage. As the voltage difference decreases, the equalization current in the inductor follows as well in the later stage of the equalization, which slows down the speed of equalization and increased the operating loss in turn. Similarly, the equalization current is mainly determined by the voltage difference between batteries in a model.[17] To mitigate the "slow down" stage in the equalization process, the analysis of currents under the voltage-balanced condition was developed as well.[18]

A resonant converter was adopted as a voltage equalizer for a series-connected energy storage system, which achieves fast equalization and low cost.[19] The process of energy distribution between the two storage modules to balance the voltage difference will cause losses after twice the power conversions. The equalizer based on the voltage multiplier can complete the equalization process by feeding energy to the low-voltage unit without two power conversions.[20] Besides, the equalizer combines a boost full-bridge inverter and asymmetrical voltage multiplier to automatically balance the voltage and reduce the conduction loss. But the current ripple of the low-voltage module will be several times that of the high-voltage module, which will limit the maximum equalization current in the equalization process. Further, an resistance capacitor diode (RCD) absorption circuit was added to the voltage-based flyback converter to eliminate the spike voltage generated by the flyback converter, thereby reducing the damage of the switching tube and improving the reliability of the system.[21]

The direct voltage acquisition circuit has a simple structure and high reliability so that the flexibility of the equalizer structure can be exerted to a greater extent. However, the estimation error of this variable is the lowest, but the inherent error is the largest, which will cause the equilibrium result to be quite different from the ideal situation. Coupled with the rapid development of current integrated circuits, the complexity of parameter acquisition and processing has been greatly reduced, so that

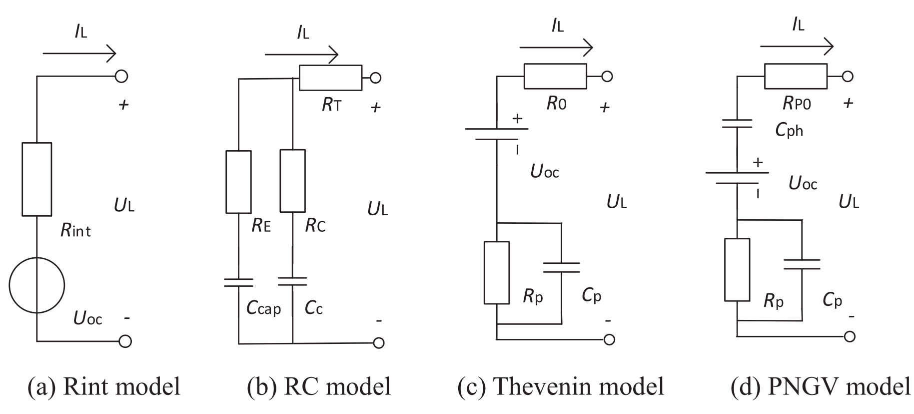

FIGURE 2 Four equivalent models of the battery

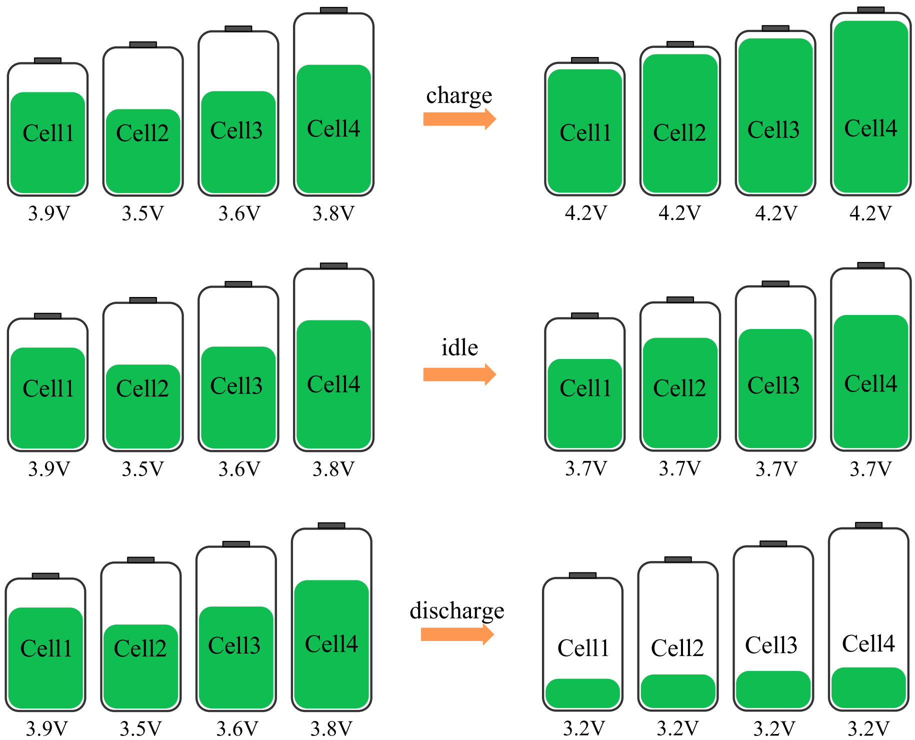

FIGURE 3 Equilibrium process based on SOV [Colour figure can be viewed at wileyonlinelibrary.com]

parameters closer to the essence of battery balance have been further widely used. Especially the equilibrium variables based on SOC has turned into a hot topic in recent years. However, the battery voltage parameter is often used as the input parameter for the calculation of parameters such as SOC, therefore, how to accurately obtain the battery voltage online still worths in-depth research.

2.2 | SOE equalization

The SOE is a key variable in the evaluation index for energy optimization and management of power battery systems. The SOE stands for the proportional parameter of the remaining power on the Wh unit scale of the electric vehicle. The direct description of battery energy supply capacity provides a more accurate basis for energy configuration and load balancing of complex energy systems.

The definition of SOE is the ratio of the residual energy to the maximum available energy,[22] which is deduced as Equation (1):

$$\mathrm{SOE}_k = \mathrm{SOE}_{k-1} - \frac{\eta \Delta E_a}{E_a} = \mathrm{SOE}_{k-1} - \frac{\eta_E U_{t,k-1} i_{L,k} \Delta t}{E_a}, \quad (1)$$

where Δt represents the sampling time, ΔE_a represents the variation of battery energy during each sampling time, E_a represents the maximum available energy of a battery, and η_E denotes the energy efficiency of a battery.

In a four-battery series connected system, the initial states and end states during equalization progress could be given, respectively, as Figure 4. The difference in remaining capacity is to express the idealized principle without considering the power loss. Normally, the remaining capacity of each cell is a little less than 2.3 Ah in idle equalization.

Previous research on SOE normally relies on a backpropagation neural network in which the model is relatively complicated and the cost is high in practice. A battery multi-state estimator based on an adaptive H-filter, and adopted recursive least squares to realize the real-time identification of battery model parameters was established in Reference 23. Whereas, the accuracy of the SOC and SOE measured by the system is limited by the accuracy of the fitting coefficient of the battery mathematical model, which requires a large amount of learning data to determine. Another concept of multi-model fusion estimation, and proposed a multi-model probability fusion estimation method with H-state observer was proposed in Reference 24. Three equivalent circuit models were merged according to the weight of the terminal voltage and its residual judgment in their expressions and considered the influence of temperature. Therefore, the estimation result is better than a single model and has strong robustness to temperature. However, the effect of battery aging on the estimation accuracy of different models has not been considered, and it lack sufficient work on the estimation of total available energy. For this, the selection of parameters in the circuit

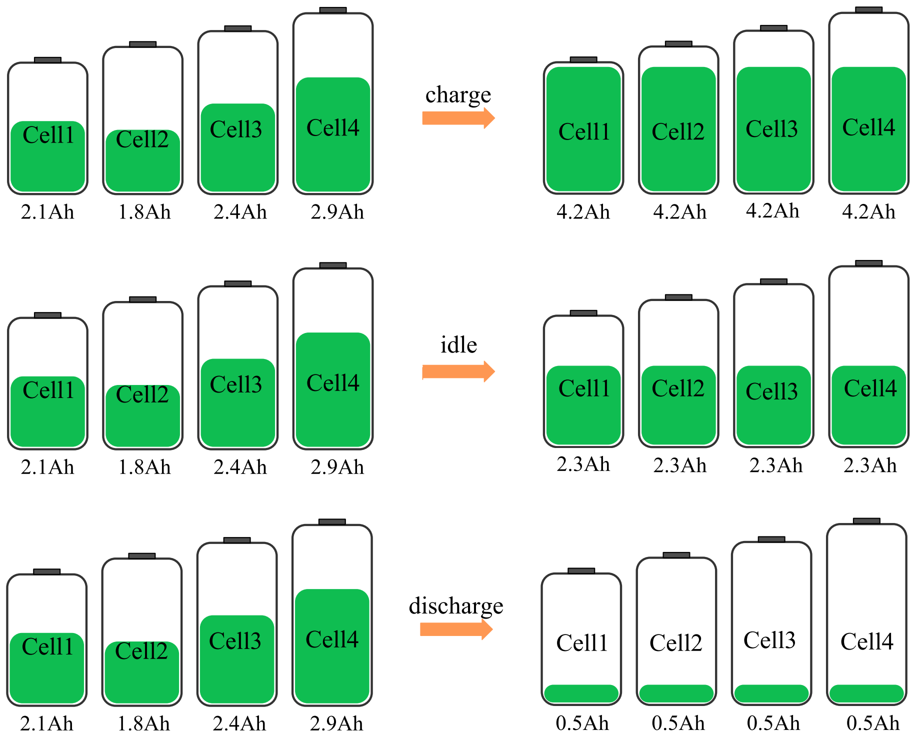

FIGURE 4 Equilibrium process based on SOE [Colour figure can be viewed at wileyonlinelibrary.com]

model should be changed accordingly to the degree of battery aging, and the estimation method of the total available energy of the battery should be optimized as well.

An estimation method based on the particle swarm optimization (PSO) algorithm to identify battery model parameters combined with an unscented Kalman filter was proposed and implemented.[25] However, the estimation stability of this method is not high enough, and prone to fall into the local optimum. To mitigate these issues, the instability or low efficiency of the algorithm needs to be further optimized. A balancing strategy based on the maximum remaining available energy to obtain more remaining available energy for electric vehicles at the expense of balancing speed was proposed in Reference 26. This method has better performance in electrical vehicles.

The online estimation of SOE has always attracted the attention of researchers in which the previous publications are mainly focused on equivalent circuit models. The existing method relies on the precise identification data, which lacks quantitative research on the impact of identification estimating error on the SOE estimation. The impact on the estimation error of SOE is analyzed and optimized by a genetic algorithm in Reference 27. Besides, the influence on the surface temperature of the battery is provided, which applies a constrained multi-parameter algorithm (CMPA) to estimate the SOE of batteries.[28]

Battery SOE and SOP are two main parameters in a battery energy storage system, which determines the high-efficiency usage of batteries. The power battery for vehicles is working in practical application, the change of the driving conditions has effects on the online estimation of the SOE. Therefore, it is more practical to predict the SOE of the power battery based on the identification of historical vehicle driving conditions.

2.3 | SOC equalization

The SOC is widely utilized in equalization technology, which is represented as the percentage of the maximum available energy in a battery. And the equation could be given as follows:

$$\mathrm{SOC}_t = \mathrm{SOC}_0 + \frac{1}{C}\int_0^t i\,dt. \tag{2}$$

In formula (2), SOC_t represents the present value and SOC_0 represents the initial value. The parameter C is the value of the capacity of the battery and i is the charge current during equalization. The consistent SOC of batteries has been achieved after the equalization process, which is shown in Figure 5.

Nowadays, the SOC has gradually become a mainstream variable for battery equalization. The accurate estimation of SOC is the foundation to enhance battery

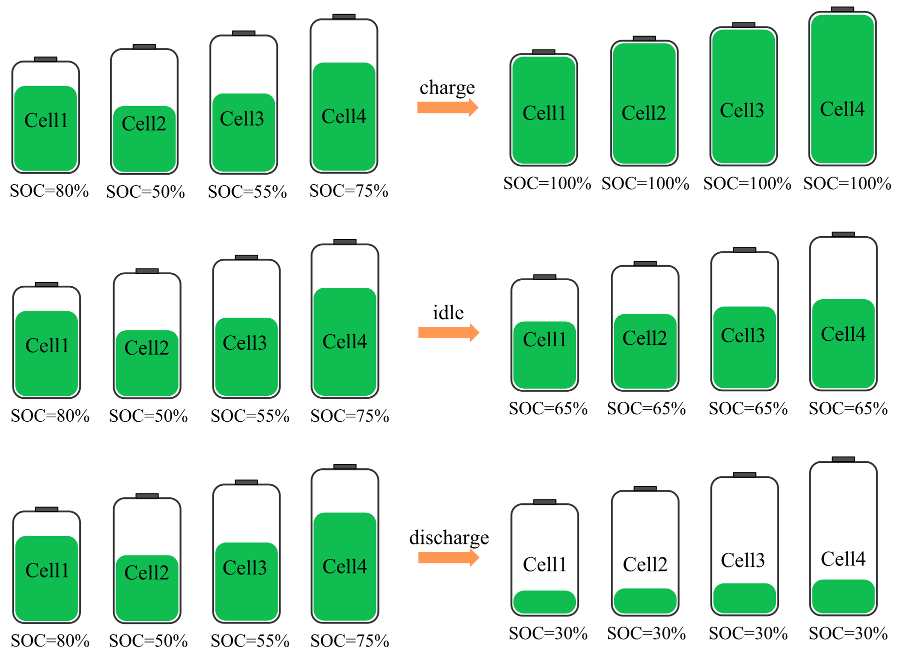

FIGURE 5 Equilibrium process based on SOC criterion [Colour figure can be viewed at wileyonlinelibrary.com]

consistency, safety, and service life, but this could be affected by the temperature and aging degree of the battery, which is normally nonlinear. Therefore, to improve the accuracy of SOC estimation, researchers have proposed many methods, including the Kalman filter (KF) algorithm, extended Kalman filter (EKF) algorithm, unscented Kalman filter (UKF) algorithm, learning algorithm, etc, which are illustrated in detail as follows.

2.3.1 | KF

The KF is suitable for linear systems, whereas batteries perform obvious nonlinear dynamic characteristics during the working process. The linearization method was proposed and then a standard KF is used to estimate the SOC based on the local linearization.[29] Only one parameter related to the SOC is contained in the output equation model, which makes the algorithm simple and time-saving. Compared with the following derivative methods, the linearization method is relatively rough and normally leads to large errors in practical applications.

2.3.2 | EKF

EKF is an extended version of the linearized KF algorithm, which linearizes nonlinear functions. The battery model and the algorithm principle of the traditional EKF were introduced in detail, and the results under the constant current and variable current conditions were verified.[30] Besides, considering the influence of battery temperature, the EKF method can also show relatively excellent performance when estimating battery SOC.[31] Further, the multi-innovation (MI-EKF) algorithm[32] is proposed to obtain a more accurate estimated SOC. The main principle of this method is to obtain information from current and previous data, to enlarge the amount of information.

2.3.3 | UKF

The UKF mainly addresses the approximation issues of EKF, which has a higher order of accuracy in estimating the mean and the error covariance of the state vector than EKF. By analyzing the principle of UKF, the experiment on equivalent circuit model verification and battery SOC is designed.[33] Based on the output data, adaptive UKF (AUKF) is employed for online model parameter identification of the equivalent circuit model.[34] Besides, the forgetting factor recursive least square is used to identify parameters of the electrical equivalent circuit model to obtain high accuracy on online SOC estimation.[35]

A joint estimation algorithm was proposed with the least-squares method with forgetting factor and AUKF.[36] Compared with the AUKF, the proposed method performs better on the accuracy and ability to the convergence of the initial error. And then, the fifth-order adaptive cubature Kalman filter (ACKF) algorithm was proposed via the standard adaptive cubic Kalman filter (CKF) algorithm, combined with the fifth-order spherical radial volume rule.[37] A more accurate SOC-OCV function and an empirical expression of battery available capacity were constructed to improve model accuracy. Compared with the traditional UKF and the ACKF, this adaptive fifth-order KF mitigated the effects of larger measurement errors and initial errors.

2.4 | SOH equalization

Although the mainstream view regards SOC as the basic variable for battery balance, it is not hard to understand that the gap in battery capacity due to later application and other reasons will lead to the disadvantage that it is impossible to achieve true balance simply using SOC. Therefore, the concept of SOH was proposed to handle the above issue. The definition of SOH is given as follows

$$\mathrm{SOH}_t = \frac{Q_{\mathrm{now}}}{Q_{\mathrm{initial}}} * 100\%, \tag{3}$$

where SOH_t is the battery's SOH now. Q_{now} is the current maximum capacity of the battery, and Q_{initial} is the initial maximum capacity of the battery. The dashed battery case represents the initial capacity of the battery, and the solid battery case represents the current capacity of the battery. The mainstream methods include the direct assessment method, adaptive approach, data-driven approach, etc, which are illustrated in detail as follows (Figure 6).

The ohmic internal resistance largely determines the capacity decay of the battery during operation. Therefore, the SOH can be estimated online by establishing the linear relationship between the ohmic internal resistance and the capacity decay. The ohmic internal resistance is utilized for determining the dynamic load curve through the Thevenin model under conditions for accurate estimation of SOH.[38] A capacity model was implemented to define the dependence of the SOC on the open-circuit voltage as the battery ages, and it could obtain better robustness under large temperature differences.[39]

The SOH estimation model based on open circuit voltage was proposed, which considers the relationship between the open-circuit voltage and SOC through a high-order polynomial with a lumped thermal model to reflect the effect of temperature.[40] However, since conventional sensors cannot directly obtain SOH, it is still difficult to make an online estimation of the SOH. In the literature,[41] a semi-supervised learning framework was implemented to estimate the ability of unlabeled data to obtain better prediction performance. The local linear reconstruction method was adopted to determine the capacity distribution of unlabeled data, and the support vector regression model was proposed for predicting the remaining useful life of the battery. However, some samples are not conducive to improving performance under this method. Therefore, adaptive filtering methods will be further developed to reduce the uncertainty of SOH prediction in the recent future.

2.5 | SOF equalization

Although SOC and SOH can, respectively, indicate the current capacity and aging degree of the battery, there is still a lack of relevant parameters for the performance of

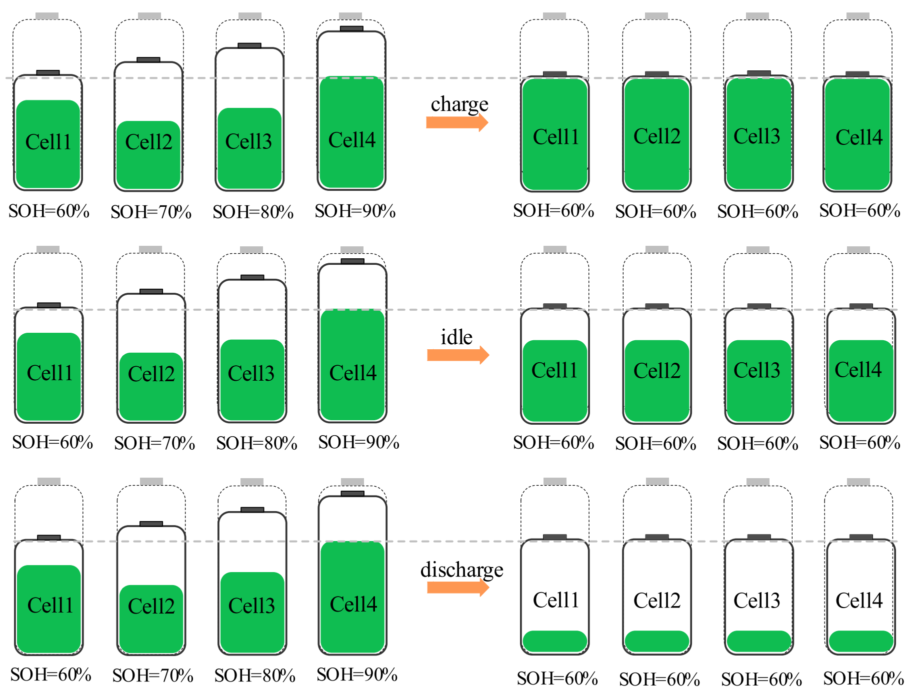

FIGURE 6 Equilibrium process based on SOH criterion [Colour figure can be viewed at wileyonlinelibrary.com]

its working state. Accordingly, the concept of SOF was proposed to describe the output capacity of the battery under specific conditions. The definitions and applications of SOF are still a little vague, not as mature as SOC and SOH. Therefore, future research on the SOF indicators of batteries is urgent, and it is worthwhile for researchers to conduct extensive and in-depth research. For now, research around SOF mainly focuses on the following aspects: variable definition and calculation methods.

In terms of variable definitions, some scholars regard SOF as the ability to output battery energy. The quantitative definition adopted in Reference 8 is the digital quantity "0" or "1", and the current-voltage is compared with the preset voltage limit. If the performance status is defined as "1" above the preset voltage limit, that is, meet the requirements; if the performance state is defined as "0" under the preset voltage limit, that is, the requirements are not met. The rough quantitative relationship mentioned between SOF and SOC, SOH is given in Figure 7.

However, the above concepts have caused obstacles to the related calculation of SOF. Therefore, the continuous neural network calculation methods to obtain highly accurate and reasonable measurements were proposed in Reference 42,43. The battery parameter identification model combining SOC, SOH, and SOF based on the above research was proposed in Reference 44. The SOF estimation algorithm could predict the maximum available power under the current and voltage requirement, with low demands for computation and storage capacity.

2.6 | Summary

Simply considering the real-time power balance method of the battery cannot meet the demand for its external output characteristics, and it has almost been eliminated. In the voltage equalization method, although the output voltage of every single battery is the same, there may be a large difference in the charge and discharge capacity that each cell obtains. The mainstream equalization variable is generally based on the SOC of the battery, which can greatly meet the physical requirements of the external circuit for the power supply. However, when the battery cell's health status varies greatly with the use in environment, the change in battery capacity should be included in the indicators of the balanced evaluation system. There are also lithium batteries with physical characteristics that meet the requirements in engineering practice, whereas their economics are no longer satisfying operating requirements. Considering the economic issues about the SOC of lithium batteries, they have gradually become the potential research direction and will witness promising prosperity in the recent future (Table 1).

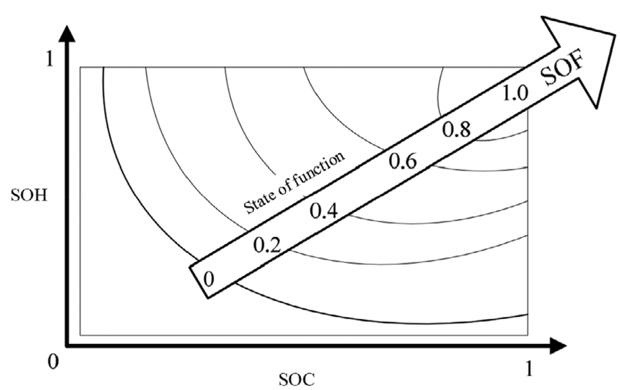

FIGURE 7 The relationship among SOF, SOC, and SOH

3 | ACTIVE CONVERTER TOPOLOGIES

The dominant converters applying for equalization could be divided into two types: passive circuits and active circuits. Whereas the passive balancing methods are normally simple and relatively low cost, the high power loss, which is dissipated via a semiconductor switch and resistor combination is the key issue. Therefore, the passive balancing methods are faded out especially in the large energy storage systems and active balancing methods perform better in dominant aspects. According to energy flow, all topologies could be divided into five categories: cell-bypass, cell-to-cell, cell-to-pack, pack-to-cell, and cell(s)-to-pack-to-cell(s).[45,46] However, from our perspective, the cell-bypass topology could belong to the cell-to-cell topology and the cell-to-pack topology is similar to the pack-to-cell topology. In addition, the pack-to-pack topology is separately divided into one category, because it does not belong to the aforementioned two topologies and has distinctive characteristics.

3.1 | Cell-to-cell topology

The cell-to-cell topology is the fundamental structure in active balancing converters. The energy delivery between the overcharged cell and the overdischarged cell is temporarily absorbed in energy storage facilities (inductors or capacitors). The equalizers could transfer the energy of the overcharged battery to the undercharged battery in turn, until the power of every single battery in the battery pack is consistent, and the equalization circuit stops operating. The traditional structure of the cell-to-cell topology is shown in Figure 8.

TABLE 1 Comparison on characteristics of different variables in battery balancing

Variables	References	Mainstream formula	Main features	Demerits
SOV	9-14	Measured directly	Simple and obtained directly	Rough equalization
SOE	15-21	$\mathrm{SOE}_k = \mathrm{SOE}_{k-1} - \frac{\eta \Delta E_a}{E_a}$	Determine the remaining mileage	Difficult to monitor online
SOC	22-30	$\mathrm{SOC}_t = \mathrm{SOC}_0 + \frac{1}{q}\int_0^t i dt$	Widely utilized for equalization	Rely on the parameter identification model
SOH	31-34	$\mathrm{SOH}_t = \frac{Q_{\mathrm{now}}}{Q_{\mathrm{initial}}} * 100\%$	To describe the loss of capacity	Immature online estimation
SOF	35-37	$\mathrm{SOF}_t = F(\mathrm{SOC}_t, \mathrm{SOH}_t)$	Drive capability	Ambiguous definition

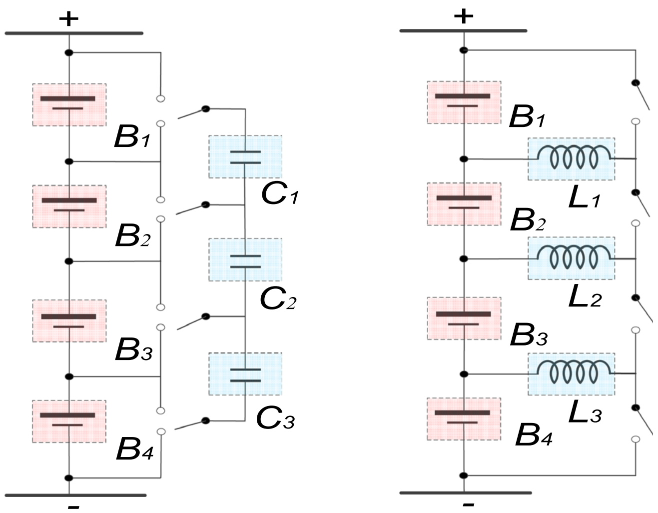

FIGURE 8 Cell to cell topologies A, capacitor-based; B, inductor-based [Colour figure can be viewed at wileyonlinelibrary.com]

High-speed switched capacitor network equalization technology was proposed to achieve the energy balance of adjacent cells in a series battery with the assistance of capacitor banks.[20] The switch-coupling capacitor balancing the topology was proposed and implemented[47-50] to achieve the energy distribution of any cell to any cell without the battery monitoring circuit. The proposed method shares a single converter to balance the energy between the unit and the module, thereby achieving a smaller size and lower cost but time-consuming process.

The traditional buck-boost topology, which is shown in Figure 9, has been improved to a lossless topology with energy transferring in Bi-directions.[51,52] The control of this topology is relatively simple and it achieves fast equalization. Whereas the system has a high equalization current and requirements on the performance of the equipped devices.

The performance of cell-to-cell balancing on the battery packs, in turn, consumes lots of time while balancing energy can only be transferred between adjacent batteries. Even if novel topologies have been proposed to handle the above issue. The point-to-point method still causes the energy flow path to be relatively long in specific conditions, making the system loss significant. Therefore, the strategy of transferring the energy of overcharged battery to all the rest batteries in the whole pack may achieve better performance.

3.2 | Cell-to-pack topology

According to the conventional single charge equalizer using the multi winding transformer, a novel switching method, which did not need voltage sensing circuits, was proposed to achieve the balance on the lithium-ion battery pack.[53] The proposed switching method could turn ON/OFF all switches connected to each battery simultaneously and would not take a long time for equalization in large series-connected battery strings. Similarly, the cell-to-pack method with a single transformer and bypass switch was developed and analyzed in detail.[54] The battery equalizer with a multi winding transformer has the advantages of easy isolation and fast balancing but is relatively difficult to be applied to a large battery string with large numbers of cells connected in series due to the serious mismatching of multiple windings, the high voltage stress on switches, the additional demagnetizing circuits, bulky size, and high implementation complexity. Furthermore, the global modular equalizer, which integrated the modular balancing and demagnetizing functions was developed in Reference 55.

Meanwhile, some improved DC converters could achieve bi-directional energy flow, which was suitable for equalization in battery strings. A novel cascade buck-boost converter was invented, which achieves the energy flows between the edge cell to the rest cells.[56] Another hybrid technology, including a power transformer and a Cuk converter was implemented with zero voltage switch (ZVS) operations reducing the switching loss.[57] However, the current ratings of switches used in the experiment are very high for reducing the conduction losses, as the peak value of the resonant current is relatively large. Besides, the dominant demerits of the above methods are complicated control logic, expanding challenges, and development

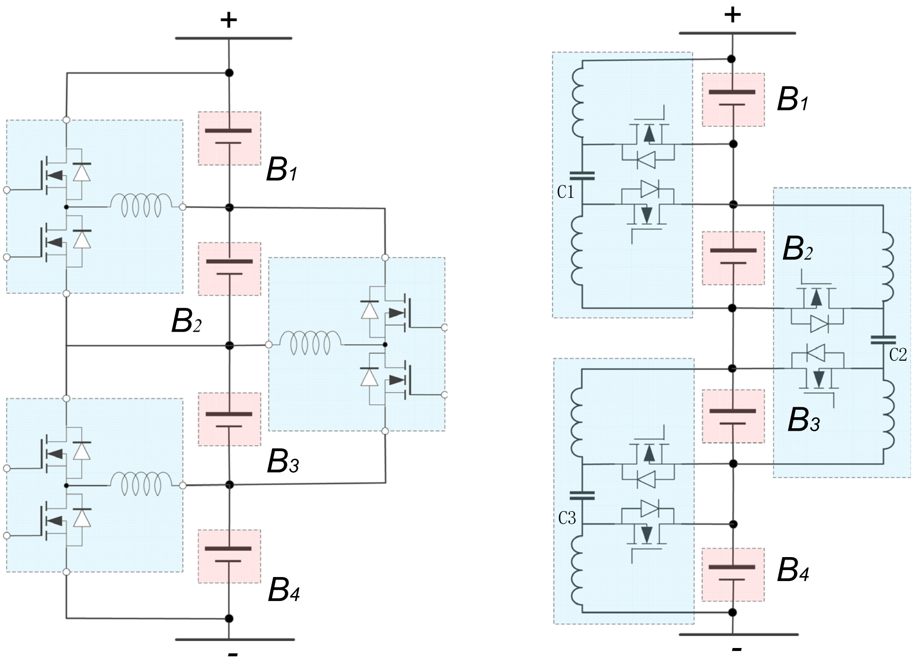

FIGURE 9 DC-DC converter A, buck-boost-based; B, Cuk-based [Colour figure can be viewed at wileyonlinelibrary.com]

limitations. It is expected that the highly integrated circuit and intelligent algorithms, such as deep learning, will resolve above issues in the recent future (Figure 10).

3.3 | Pack-to-pack topology

Considering the complex condition, the cell-to-pack topology could probably be weak in a situation when the unequal cells are dominant in strings. Therefore, the motivation is to propose more flexible converters with convenient energy route. Figures 11 and 12 show some feasible circuit topologies in which the energy flow is between any pack to pack in the whole strings.

The charging and discharging equalizer based on the buck and boost-buck chopper circuits for the battery pack is analyzed in.[58,59] It is simple to control the balancing circuit and easy to be realized; the balanced battery cell is selectable and the balancing energy is bidirectional; the balancing current is controllable. This topology has been improved in,[60] in which the diodes are replaced with metal-oxide-semiconductor field-effect transistor (MOSFET) to achieve a bidirectional flow of energy. It makes the balancing process more flexible, but it inevitably complicates the control method as well.

A novel interleaved equalization method and its natural balancing control were provided in detail.[16] It should be indicated that similar topologies that enable hybrid equalization are attractive for researchers in terms of equalization speed efficiency, and flexibility. The demerit of this kind of converter is that the limitation of the boost ratio of the circuit, which means when the top or button

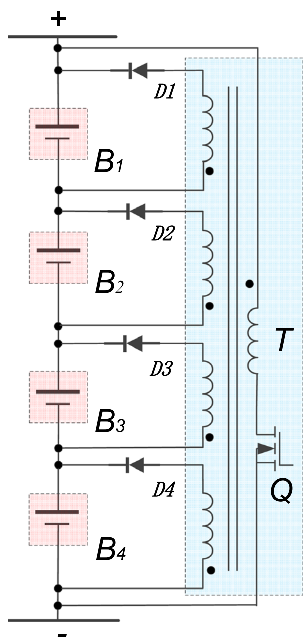

FIGURE 10 Cell-to-pack topology with transformer [Colour figure can be viewed at wileyonlinelibrary.com]

several cells have overcharged the power of which could not be delivered to the rest of the whole cells due to the voltage of the power source. A group of coat circuits for basic DC/DC converters to improve voltage conversion ratio has been provided in Reference 61. The voltage conversion ratio of the DC/DC converters has been improved effectively, and a wide range of input-output voltage conversion can be realized; the number of basic units in the

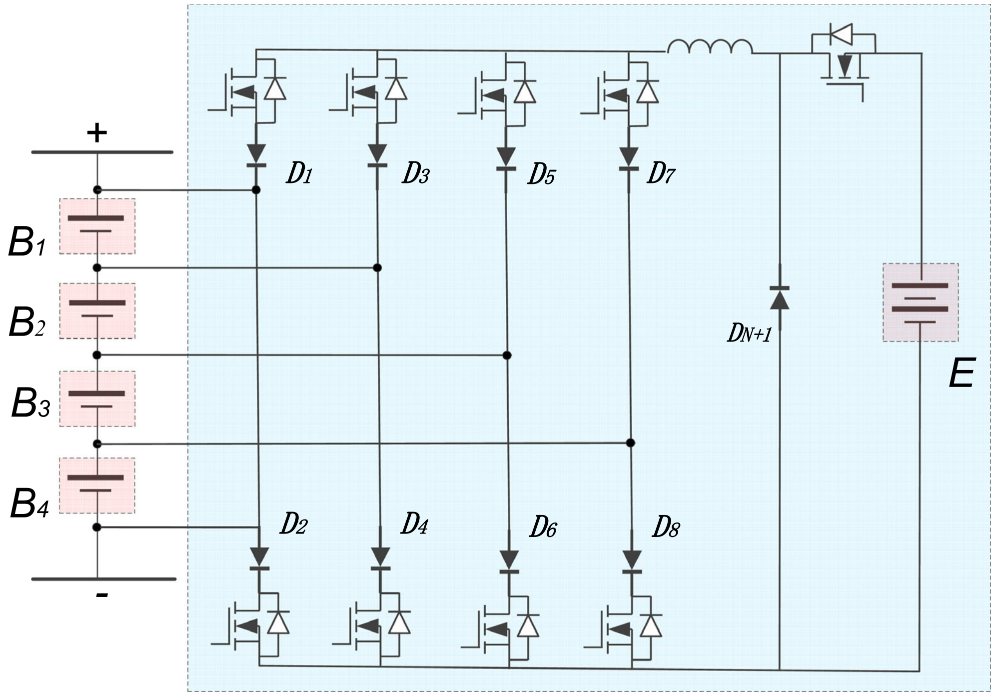

FIGURE 11 Cell-to-pack topology with improved buck-boost converter [Colour figure can be viewed at wileyonlinelibrary.com]

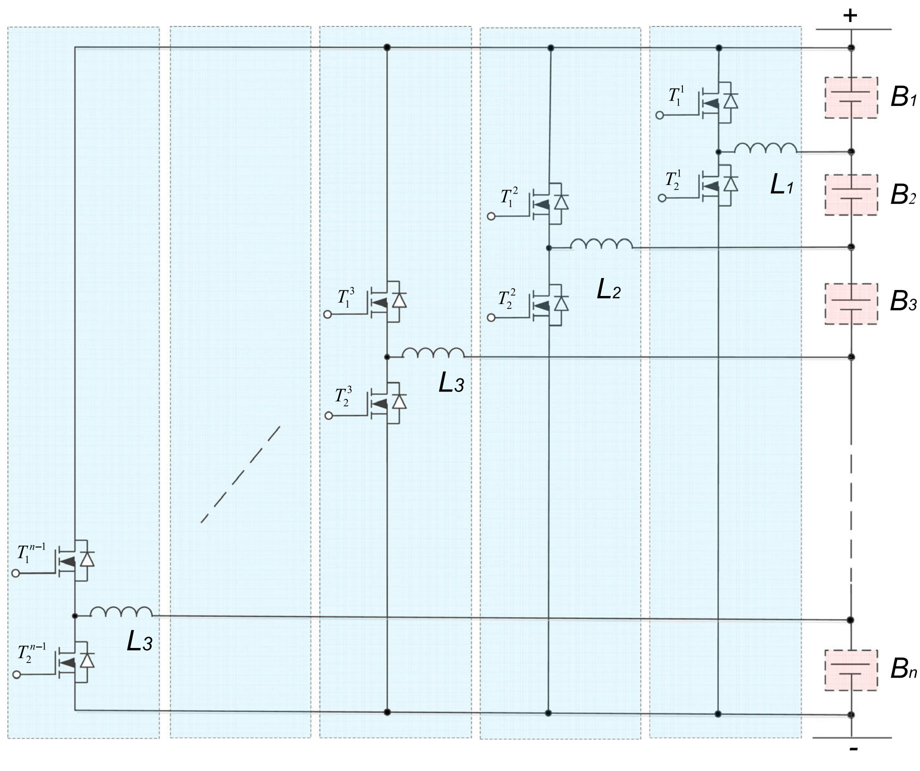

FIGURE 12 Multi-phase and multi-layer converter for equalization [Colour figure can be viewed at wileyonlinelibrary.com]

coat circuits can be optimized to satisfy the requirements of various applications as well.

Based on game theory, another paper compares the equilibrium process of the circuit to a full-information static game and establishes a mathematical model describing the correspondence between the duty cycle of each switch in the equilibrium unit and the energy change of every single battery.[62] Solve the Nash equilibrium solution of the game model to obtain the optimal control scheme of the equilibrium circuit. The equalization process in Reference 63 is matrixed so that each equalizer can operate synchronously, which reduces the extra equalization loss caused by energy circulation compared with the natural equalization method.

3.4 | Summary

To analyze the characteristics of the equalization circuit from the source and destination of the energy transfer, not only the influence of the circuit structure on the battery equalization is considered, but also the path of the energy flow can be optimized to improve the overall performance of the equalization system (Table 2).

The structure of the cell-to-cell type is simple and easy to control, whereas the long energy flows will lead to high power loss; the cell-to-pack approach effectively shortens the energy transfer flow, some cells of the battery pack will be repeatedly charged or discharged, which cause adverse effects; therefore, the pack to pack topologies were proposed to handle the above and perform better especially for large scale series battery system. However, since the switching device needs to bear the voltage and current stress of the entire battery pack, the requirements for the components of the equalization circuit are much higher.

4 | MODULAR METHODS

In addition, the main factor that affects the effectiveness of the series lithium battery equalization system is the connection mode in the equalization module. This chapter compares and analyzes the single-layer-based, modular-based, and hybrid-based topologies of the equalization structure, and then the systematic evaluation with graph theory was provided and analyzed in detail.

4.1 | Single-layer-based method

Based on the above analysis, the distributed equalizers (such as bypass converter in Reference 49-51) and centralized equalizers (such as single transformer in Reference 53-55) are feasible and widely used for small or middle battery systems due to their simple control and fast equalization. Figures 13 and 14 are two mainstream topologies for the single-layer-based method.

Furthermore, the relationship between the number of batteries and the average efficiency (AE) of the converter is derived as Equation (4) in Reference 64.

$$\mathrm{AE} = \frac{2n\eta(1-\eta) - 2\eta(1-\eta^n)}{n(n-1)(1-\eta)^2} \tag{4}$$

where n is the number of battery cells in the battery pack, η is the efficiency of the sub-module equalizer. In an ideal state, the efficiency of each sub-module is considered equal and equal to η. Besides, to make the derivation of average efficiency have a wide range of adaptability, it is assumed that each battery in the battery pack has the same probability of energy anomaly, and the distribution of battery energy anomalies obeys normal distribution. For a single-layer distributed balance structure, the relationship among the AE, the number of batteries, and the efficiency of sub-modules are shown in Figure 15.

It can be concluded that for a single-layer distributed topology, as the scale increases, the AE will drop sharply. Although the efficiency of the sub-modules can be improved by designing efficient transformation topologies and ultimately the overall efficiency of the system, it will become extremely difficult to further improve the efficiency. Therefore, a modular hierarchical grouping equalization strategy is proposed to alleviate the above-mentioned problems. It is worth mentioning that although the average efficiency in the corresponding centralized method is only the square of one tower, it will not decrease as the number of batteries increases. But it must be admitted that in a centralized topology, each switching device needs to withstand the voltage and current stress of the entire battery pack, which puts forward extremely high requirements on the performance of the device, which makes the system hardware cost more expensive.

TABLE 2 Comparison of typical equalization equipment

Type	Main feature	References	Merits	Demerits
Cell-to-cell	Capacitor or inductor Internet	42-45	Simple and easy	Low efficiency
	DC converter	46,47		Complex on control
Cell-to-pack	Transformer	48-50	Fast and direct	Large volume and overweight
	Cascade converter	51,52	Low power loss	Not flexible
Pack-to-pack	Switch array	53-55	Flexible	High device cost
	Interleaved converter	56,57	Synchronous operating	Loop loss

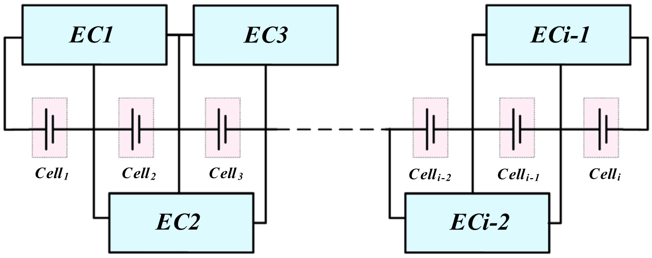

FIGURE 13 The structure on the distributed single-layer-based converter [Colour figure can be viewed at wileyonlinelibrary.com]

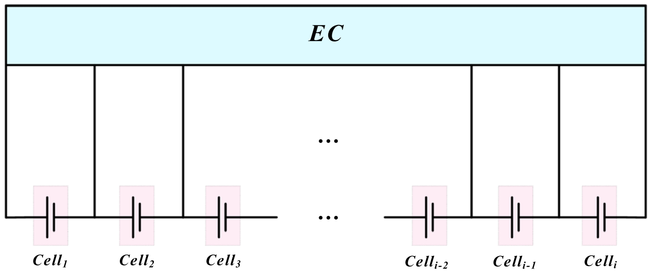

FIGURE 14 The structure on a centralized single-layer-based converter [Colour figure can be viewed at wileyonlinelibrary.com]

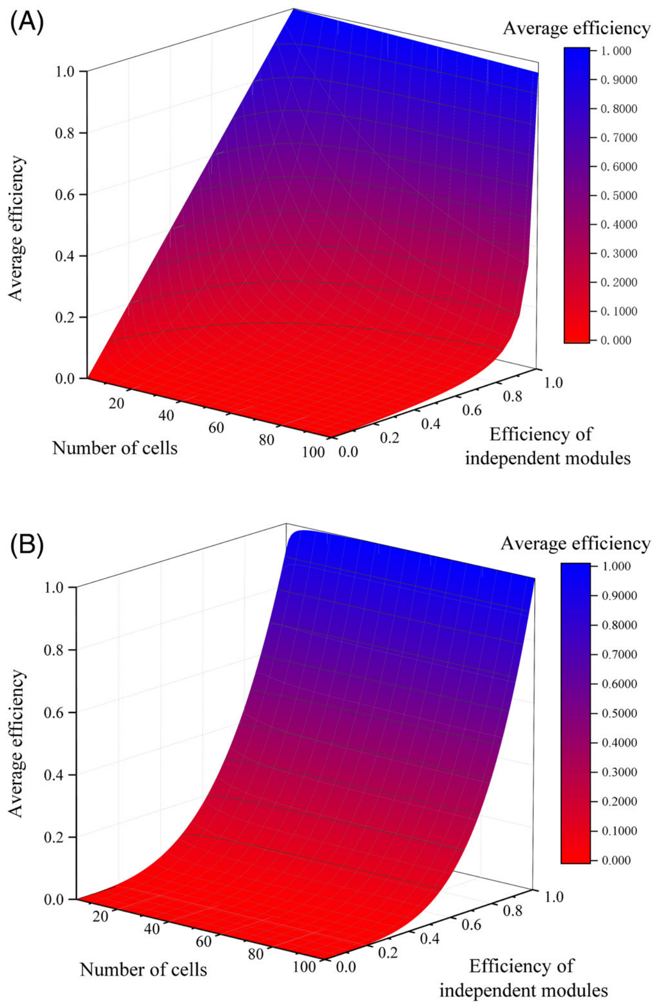

FIGURE 15 The relationship among AE, number of cells, and efficiency of the independent equalizer A, the distributed single-layer-based converter B, Multi-phase and multi-layer converter [Colour figure can be viewed at wileyonlinelibrary.com]

4.2 | Modular-based method

The single-layer equalization topology often leads to an extension of the energy transfer path due to the excessive number of batteries, which increases the equalization time and the loss in the energy transfer process, which ultimately affects the efficiency of the equalizer. The modular multi-layer balanced topology design can effectively alleviate the above problems, and the energy of the battery can be quickly transferred in the respective modules.

Normally, the same structure could be applied in the bottom and top layers of the equalization system.[17] The batteries in a sub-modular are balanced first and then the equalization is between this modular and other modular. The layering and grouping modular strategy can alleviate the lengthy energy path caused by the single-layer equalizer structure, thereby achieving low-loss fast equalization. Besides, the middle layers could be inserted into the system when it comes to large battery strings. Another thing worth mentioning is that the number of batteries in each module can be inconsistent, to respond more flexibly to the requirement of engineering projects.

Furthermore, the cascading method of the same module was proposed and verified in.[65] In this design, each battery can exchange energy with some batteries in the battery without traversing different levels of equalization modules, which improves the equalization speed. However, because the number of batteries balanced by each layer of converters is different, the parameter design of each equalizer needs to be designed independently, which increases the control complexity of the system (Figure 16).

How to select the appropriate number of group members has always been a key issue in modular designing. The characteristics of single-layer bypass and complete dichotomy modularization were analyzed in detail, and a compromise topology was proposed in Reference 66. The bottom converters transfer energy between B_{2n-1} and B_{2n}, and the top bypass converters were applied for balancing adjacent two-battery packs, which are shown in Figure 17.

4.3 | Hybrid-based method

It is naturally considered that the combination of equalizers is not just a simple series connection or stacking of the same module. The utilization of various topologies at different levels may result in higher balanced returns in speed and efficiency (Figures 18 and 19).

A hybrid converter combining dichotomous and cascaded topology was proposed in Reference 67, in which the modular equilibrium control strategy is used in the first stage and the second stage, the energy average control strategy is used in the remaining stages. Furthermore, the charging and discharging times of a single cell, not only each circuit, are reduced a lot compared to a single topology modular. It is not difficult to conclude that although this method is more effective than stacking with a single topology alone, it lacks further discussion and analysis on how to further optimize the equalization time.

About the combination of the bottom-layer equalizer and the upper-layer equalizer, an in-depth discussion is implemented in Reference 68,69. In the bottom module, the cell-to-pack topology can be used to quickly balance the local battery energy; in the upper module, the pack-to-pack topology can be used to balance the battery energy between non-adjacent modules. It is not difficult to foresee that even if it is an equalizer on the same layer, different topologies can also be selected, which will be more flexible to achieve the energy balance of the battery pack. However, the parallel use of different equalizers will bring no small trouble to the system control. Therefore, a selection switches topology is designed and developed.[70] In this design, the concept of layering and grouping is blurred, and replaced by the battery to be balanced determined by the selection switches. In other words, in the proposed topology, the three types of balance of cell-to-cell, cell-to-pack, and pack-to-pack can be achieved through selection switches, which is quite excellent in the flexibility of energy flow.

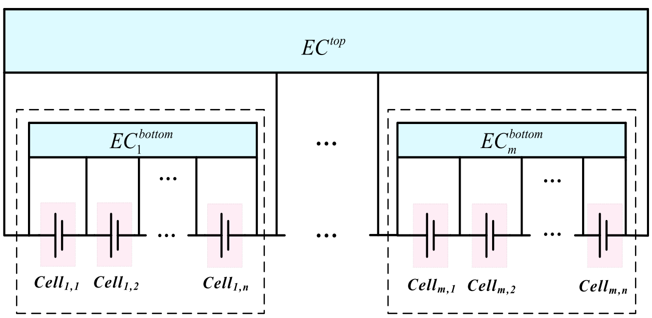

FIGURE 16 Module-based battery charge equalization topology (centralized) [Colour figure can be viewed at wileyonlinelibrary.com]

4.4 | Evaluation based on graph theory

There are various types of equalization circuits and complex circuits, and the equalization effect depends largely on the inconsistency of the battery in actual working conditions, which makes it difficult to compare the performance of the equalization circuit systematically. As a mathematical analysis tool, graph theory can illustrate the relationship between transactions more intuitively. When it was applied to the analysis of battery balancing circuits, it delivers the overall performance of the circuit more intuitively and systematically.

The graph theory method is initially applied to cell-to-cell circuits, and the average equalization efficiency of several mainstream circuits was analyzed.[64] The relationship between the average system efficiency and the number of cells and the efficiency of the independent equalizer is derived and made the comparison. Besides, the effects on the number of cells in the modular equalization were hierarchically sealed, which found a basic theory for the application of graph theory in the cell equalization system (Figure 20).

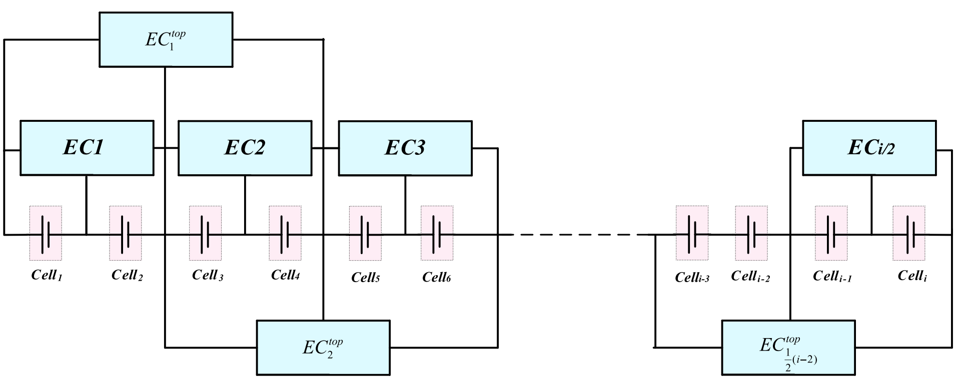

FIGURE 17 Module-based battery charge equalization topology (distributed) [Colour figure can be viewed at wileyonlinelibrary.com]

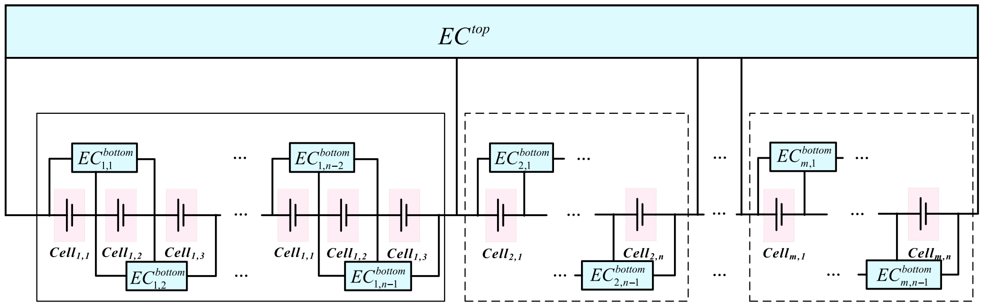

FIGURE 18 Hybrid-based method (button layer: bypass; top layer: cell-to-pack) [Colour figure can be viewed at wileyonlinelibrary.com]

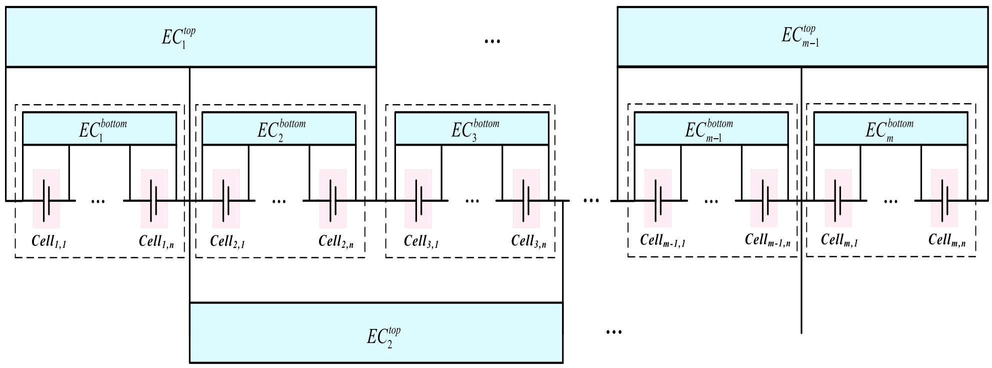

FIGURE 19 Hybrid-based method (button layer: cell-to-pack; top layer: bypass) [Colour figure can be viewed at wileyonlinelibrary.com]

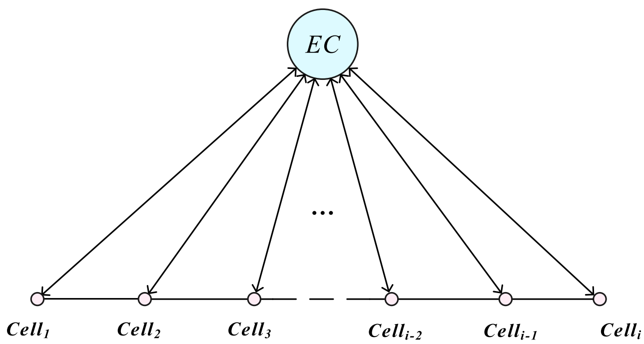

FIGURE 20 Single-layer based converter in graph theory [Colour figure can be viewed at wileyonlinelibrary.com]

Furthermore, the determinants of the average efficiency of multiphase interleaved converters by simplifying the equalization circuit into a graph.[71] Meanwhile, the relationship between the average efficiency of the system and the efficiency of the independent equalizer is further considered, and its conclusion is helpful to provide design guidance for the design of large-scale battery equalization systems. However, the consideration of battery inconsistency is deeply simplified, and the energy route of two batteries with abnormal energy is considered, which is different from the actual working conditions. Hence, it is necessary to further consider the average efficiency of the system under the abnormal distribution of multi-battery energy.

A graphical model for evaluating the status of a series-connected Li-ion battery pack is established to release the burden on calculation in Reference 72. The model is founded by a 2D diagram, with the electric quantity "E" and the capacity "Q" as its axes, therefore, called the "E-Q diagram". The novel graphical diagram presents the dynamics of cell variations linearly, thereby benefiting the design and management of the battery pack (Figures 21-23).

4.5 | Summary

Direct structure to simply connect the equalizers in series is a dominant choice, whereas the energy flow path is overlong when there are a large number of battery cells, resulting in a low average system efficiency, which is only suitable for the balancing situation with a small number of batteries. Modular hierarchical grouping can effectively improve the overall balanced efficiency while avoiding the risk that all components need to bear high stress. Whereas for a single topology stack, there will still be a low-performance balance under adverse conditions, so considering the actual working conditions, the use of a mixed layering of multiple topologies combined to weaken the adverse conditions as much as possible. Finally, with the application of graph theory analysis methods, systematic comparison, and evaluation of the above topology design are demonstrated.

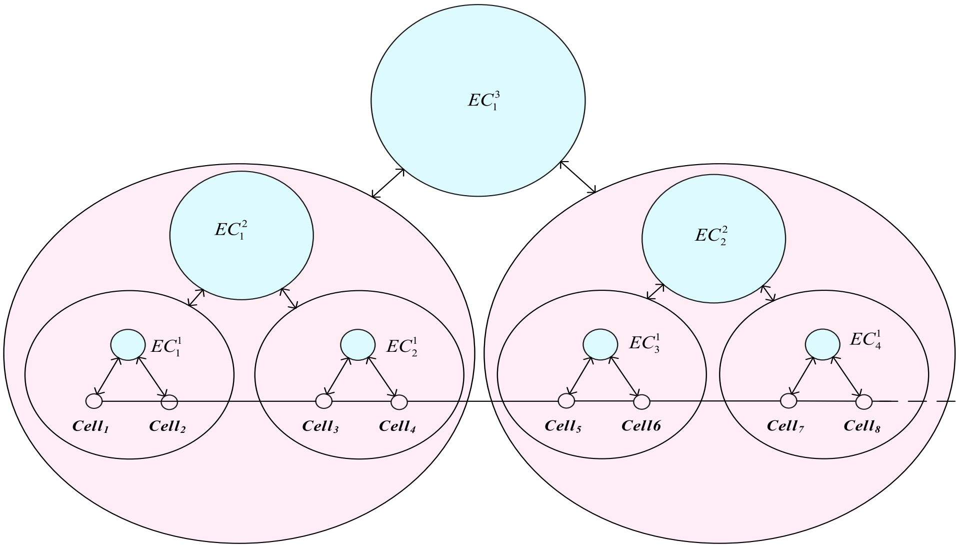

FIGURE 21 Multi-layer multi-modular based converter in graph theory [Colour figure can be viewed at wileyonlinelibrary.com]

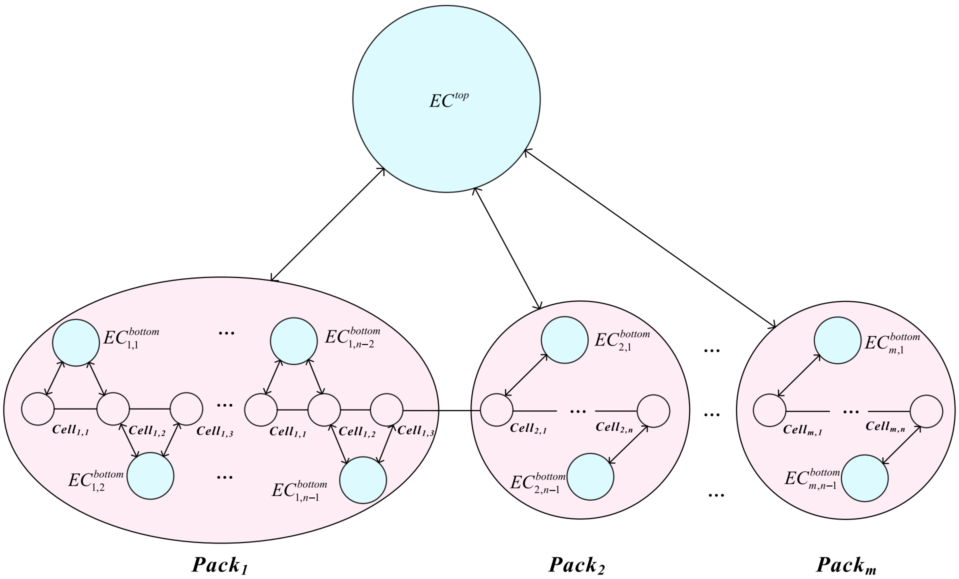

FIGURE 22 Hybrid-based converter in graph theory (bottom layer: bypass; top layer: centralized) [Colour figure can be viewed at wileyonlinelibrary.com]

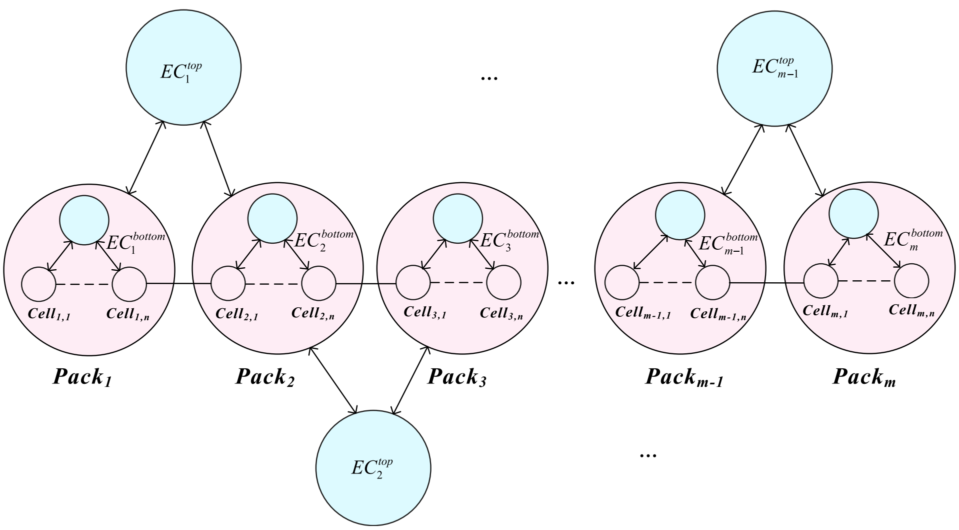

FIGURE 23 Hybrid-based method in graph theory (bottom layer: centralized; top layer: bypass) [Colour figure can be viewed at wileyonlinelibrary.com]

5 | KEY ISSUES AND FUTURE RESEARCH

5.1 | Variables

As a criterion for the end of the equalization process, the appropriate selection of variables will directly determine the equalization performance of the lithium battery pack. The research on variables has also moved from the characterization of the battery to its intrinsic properties. Although SOC and SOH have been able to explain the current energy state of the battery to a large extent, they lack a description of the output capacity of the battery in a specific state. The introduction of the SOF concept fills the gap in the description of battery output capability to a certain extent, and its definition is currently unclear and has not been unanimously agreed upon by the majority of researchers. In the future, while the SOF definition is being continuously improved, more parameters will be proposed to express the intrinsic characteristics of lithium batteries. This will serve the construction of lithium battery equalization systems and provide a guide for researchers to understand battery behavior.

5.2 | Topologies

It is necessary to analyze the performance of the converter circuit from different angles, and seek a balance point among various performance indicators, to find the most suitable topology under the given conditions. Among them, flexibility is the primary consideration. Compared with energy transfer between a single battery and a single battery or energy transfer between a single battery and packs, the path of any cell(s) to any cell(s) undoubtedly has relatively superior performance. But correspondingly, its control complexity and the number and cost of components have been increased. To further realize the low loss of the circuit, for the inherent operating loss of the circuit components, the power electronic technology, new circuit component materials, and other means are used to effectively reduce the energy loss and improve the working efficiency of the equalization circuit. For example, phase-shifting resonant soft-switching technology can reduce switching stress and switching loss, and wide bandgap devices made of materials such as silicon carbide or gallium nitride can achieve stronger withstand voltage, temperature resistance, and smaller switch internal resistance. In the future, with the design of combination equalization schemes such as active and passive equalization circuit combination, auxiliary equalization, and layered equalization, multiple equalization methods are complemented, thereby effectively improving the defects caused by single equalization, and realizing a composite equalization that combines the advantages of multiple equalization methods.

5.3 | Modular

Compared with ordinary small-capacity battery packs in series, large-capacity battery pack balancing systems generally have the characteristics of multi-level, large current, high efficiency, and centralized control. The traditional single-layer balanced topology can hardly meet the requirement for the application of large-scale lithium battery energy storage systems. The strategy of dividing into groups and balancing by selecting the optimal number of modules and circuit levels, to achieve the optimal design of the long battery string balancing topology, can alleviate the monomer difference of the large-capacity battery pack to a certain extent. Furthermore, the combination of different topologies applied to different layers, and even a composite balanced topology that can mix multiple structures on the same layer will provide a feasible solution to the issue of complex large-capacity battery packs. But this will undoubtedly lead to problems such as an increase in control complexity while achieving efficient equilibrium. Therefore, how to find a balance between all parties will become a hot spot in recent future research.

5.4 | Recycling utilization

Battery equalization as an effective method to deal with the inconsistency of battery cell energy cannot be done once and for all. There will still be some batteries that cannot participate in battery pack equalization due to their performance differences and need to be retired for other purposes.[11,73] For example, the single cells in the battery pack of new energy vehicles no longer meet the output capacity of driving motors and other equipment, but they can still be used as energy storage equipment for photovoltaic power generation systems. Nowadays, research on the recycling utilization of decommissioned batteries when the production and application of lithium batteries have been greatly increased, lithium batteries can be fully utilized to reduce environmental pollution caused by the direct scrap.

6 | CONCLUSION

Increasing electric vehicle penetration leads to significant challenges in EV battery disposal. Reusing retired batteries in distributed energy systems offers resource-circular solutions. The characteristics of the battery pack are closely related to the quality of its balance management system, and this paper reviews several key issues related to the series balance of lithium battery packs. The equalization system is presented from the perspective of equalization variables, circuit topologies, and modular methods, and the advantages and disadvantages of each method are summarized. Finally, the current dilemma of battery balance management research and the future potential research directions have prospected.

1. In terms of equilibrium variables, although mainstream research usually uses SOC as a benchmark or core criterion, because lithium batteries are used as chemical power sources, their internal reactions are complex and have a greater impact on external characteristics. Therefore, it is particularly important to consider whether to meet the equilibrium index in consideration of factors such as battery capacity and recyclable charge and discharge times. Although this is safer and more reasonable, it will undoubtedly increase the burden of system analysis and processing. The application of high-performance computing in the future may be able to provide a feasible solution for accurately determining the equilibrium state of the battery.
2. Compared with the traditional classification based on the structure of the equalization circuit, this article divides the equalization circuit into cell-to-cell, cell-to-pack, and pack-to-pack according to the different energy transfer objects. The cell-to-cell method often requires equalization in sequence, and the process is relatively time-consuming; The cell-to-pack method can save equalization time because it transfers the energy of the battery string as a whole, but abnormal batteries normally need to be repeatedly charged and discharged; the pack-to-pack method is relatively novel, and it can flexibly adjust the partial battery packs in the battery pack through appropriate switch tube combinations Perform equalization. The circuit structure is constantly innovating, and its topology has become relatively complex while also setting higher standards for control strategies. Therefore, the more flexible structures and advanced control will be applied to battery equalization technology.
3. Single-layer equalization circuits normally lead to low equalization efficiency due to the excessive number of batteries. Therefore, proper layered grouping and equalization of the battery pack is an inevitable choice to improve system efficiency. At the same time, using different equalization circuits in different layer groups can often yield more efficient results than choosing a single topology. In the selection of grouping and circuit topology, the introduction of graph theory methods is expected to provide effective solutions to key problems, which are worthy of further discussion in the future.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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