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A comprehensive review on inconsistency and equalization technology of lithium-ion battery for electric vehicles

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Abstract: The rapid growth of transportation demand has been enlarged strongly which has promoted electric vehicles powered by lithium-ion batteries. However, the inconsistencies within the battery pack will deteriorate over the lifecycle and affect the performance of electric vehicles. Therefore, various thermal management systems and equalization systems have been applied in battery management system to deal with the inconsistencies, extend battery service life, and improve safety performance. This review summarizes the origination of inconsistency within lithium-ion batteries from production to usage process, and then introduces the classification methods and application scenarios of the balance management system in detail. Based on the circuit topology, equalization systems can be classified into passive and active topologies. Active topologies are widely researched due to the advantages of high equalization efficiency and high speed, and the state-of-art innovations are presented and compared from the prospective of circuit, energy flow, efficiency and system complexity. In addition, this review focuses on the mainstream equalization strategies based on the analysis of balancing variables and control algorithms in terms of efficiency, complexity and stability, especially in the areas of variables optimal selection and advanced control algorithms. It is expected that innovations such as cloud control methods and hybrid balancing systems equipped with thermal management will become the future direction of lithium-ion equalization technologies.

Key words: Electric vehicles; Li-ion battery; Cell imbalance; Equalization control

1 Introduction

Concerns about environmental pollution and energy crisis help promote the development of electric vehicles (EVs), including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles

(PHEVs), and pure electric vehicles (PEVs) [1-3]. EVs have developed rapidly due to their low noise, less-emission and high energy efficiency. Energy storage systems (ESS) are essential elements in EVs. Lithium-ion battery (LIB) is the most popular ESS in EVs because of the merits of high energy/power density, long cycling life-time and environmental friendliness [4, 5].

Development of LIBs in materials and production has greatly improved the performance of EVs. In 2016, Nissan Leaf had a stated range of 170 km, and now Tesla Model S and the Opel Ampera-E come with the nameplate ranges over 500 km [6]. However, the battery performances such as available capacity and power ability will decrease during the usage [7], which resulting in a reduction of the driving range [8]. Degradation of LIBs also has a critical impact on the safety behavior. Compared with fresh cells, aged batteries will undergo thermal runaway possibility at lower temperature [9, 10], leading to higher safety risks.

The battery packs in EVs consists of large number of LIB batteries grouped in series and in parallel to provide sufficient power and desired energy for the EVs. However, the battery internal characteristics including initial capacity, internal impedance, physical volume, self-discharge rate, etc., and external conditions, such as ambient temperature, are always inconsistent in practical applications [11]. At the pack level, variations in cell parameters can lead to subsequent acceleration of the degradation [12], with negative impact on the available power, capacity, lifespan, etc. The imbalance can deteriorate with the battery degradation and may further lead to the risk of thermal runaway [13-15]. Therefore, battery equalization, which can enhance the pack safety and performance, is a critical technology for reduction of the cell imbalance [16].

Equalization is also critical for the second use of retired LIBs. Batteries with a capacity degradation of 20% should be replaced to guarantee safety and driving range of EVs [17-19]. Repurposing the retired LIBs for electric bicycles, excursion vehicles and energy storage systems in electricity grid, can generate great economic and environmental benefits, but retired LIBs with poor consistency are not worthy being re-used in storage applications [20, 21] due to the risk of rapid aging and thermal runaway. Thermal management system (TMS) and equalization manage system (EMS) can effectively improve the inconsistency of LIBs for both first life in EVs and second life applications [18, 22].

Equalization circuit, or equalizers, combined with equalization strategies, can help to overcome the pack imbalance problem. Various equalizers have been developed recently [23]. Although different EV applications have different requirements, the hardware topology design is normally constrained by performance indexes including cost, size and reliability. Similarly, the software control strategy needs to tackle the issue of the nonlinearity, hysteresis and strong coupling characteristics. In spite of the progresses, existing equalization solutions can hardly meet the requirements of size, cost, computational complexity and reliability, which will be discussed in this paper to identify the existing technology gaps and to facilitate future research. Therefore, it is essential to summarize the cause of inconsistency reasons and the status of equalization topology and algorithms, to provide guidance for the design of BMS with high safety, long life and reasonable cost.

2 LIBs Inconsistency

To satisfy the demand of EVs in voltage, power and energy, packs usually contain hundreds or thousands of cells. While, the differences of characteristics among these cells are inevitable [24]. The barrel effect can illustrate the impacts of inconsistencies in battery pack, as shown in Fig 1. As shown as Fig. 1a, the available discharge capacity of a battery pack is determined by the cell with the lowest capacity, where the battery pack will stop discharging if any single cell reach the end of discharging. Similarly, the available charge capacity of a pack, as shown in Fig. 1b, is restricted by the LIB cell in the pack with the lowest available charge capacity, where the pack would stop charging if any cell reaches the end of charging. Therefore, the available charge/discharge pack capacity is strongly influenced by pack inconsistencies.

Besides that, the inconsistencies are time-varying and coupled with various factors, especially battery degradation. The nonlinear aging characteristics of LIBs will gradually affect the pack inconsistency [25]. Although the battery pack can have less than 3% initial capacity mismatch [26], the inconsistency cannot be self-eliminated and has a tendency for enlarging which has similar specialization with the positive feedback effect. The increasing inconsistency may lead to premature degradation of the pack and increase the possibility of overcharging and over-discharging during the cycle, leading to increased risk of thermal runaway [27].

2.1 Inconsistency origination

The origination of inconsistency of LIBs usually can be separated into production process and usage process. The former can be caused by variances in the raw materials, manufacture equipment and procedures, which will lead to inconsistent LIB parameters. The latter mainly originate from environmental differences during battery usage and storage. Both the inconsistency could influence the performance of the battery pack.

2.1.1 Inconsistency caused by cell production

The production process of LIBs consists of mixing slurry, coating, cutting, winding, assembling and electrolyte injection, where each step may cause variances and affect the inconsistency of the LIBs. For instance, the non-uniformity of the mixing slurry can cause subtle defects in the microstructure, which may in turn affects the macro performance. Due to material differences, equipment accuracy, and uncertainty in the manufacturing process, the characteristics between different batches or even the same batch of batteries will inevitably be different. The other influence of initial inhomogeneity includes initial capacity and internal resistance, lithium-ion concentration, separator thickness and so on.

The inconsistency caused by the production process cannot be eliminated completely. However, Screening methods can sort out the batteries with good consistency, thereby effectively improving the reliability, safety and lifespan performance of packs. Screening methods can be utilized based on criteria such as capacity, internal resistance, and self-discharging rate to significantly improve the pack performance [28].

2.1.2 Inconsistency caused by module and pack assembly

Besides the cell manufacturing process, the assembly technology of modules and packs is also of essential for maintaining the consistency. For example, the degree of tightness will affect the stress on batteries, and the interval between batteries may affect the dissipation of heat generated by batteries. More research has been performed, such as Ji et al. [29] studied the effect of cell intervals on module uniformity. Results of heat-electrochemical coupled model illustrate that variation of intervals can effectively improve homogeneity for 18650 modules, and the temperature difference can be reduced by 13% when the cell intervals are adjusted to 3~5.5 mm.

The temperature distribution could greatly influence the battery inconsistency, which is related to the assembly layout of the pack. The batteries can generate heat during operation, which cannot dissipate instantaneously and further increase the battery temperature. In addition, the heat exchange environments of batteries are also different, for example, the external batteries have large heat exchange areas, while the internal cells can only exchange heat with adjacent batteries. Therefore, the assembly layout could lead to different temperature distributions, which will lead to inconsistencies between batteries.

2.1.3 Inconsistency caused by usage

Batteries in the same pack usually tempts to maintain the uniformity after initially assembly, but the inconsistency may be gradually enlarged, whether storage or usage, reducing the performance of the pack. Both physical and chemical stresses may accumulate gradually during battery usage [30]. The degradation process is very complicated, including various aging mechanisms and their interactions occurring inside the batteries, and the degradation of electrodes is the main factor causing the decay in battery performance. Factors such as temperature, current, state of charge (SOC) can significantly affect the active materials and microstructures [7], and the variation between these factors will inevitably exacerbate the inconsistencies within the battery pack.

Temperature is a critical factor affecting the degradation rate. The temperature difference will cause different aging rates between cells, thereby aggravating the inconsistencies within the battery pack. Both high and low temperatures can accelerate degradation of the battery. Working or storing under high temperature can accelerate the side reactions, and charging at low temperature may resulting in lithium deposition and even the growth of dendrite [8]. Besides, the differences of internal resistance and heat capacity between batteries will result in uneven temperature distribution within the pack. Coupling with forced convection and coolant channel, the uniform heat dissipation will enlarge the difference of degradation between individual cells and therefore affect the life and available capacity [31]. Phase change material (PCM) can also be applied for battery pack thermal management, which can decrease the maximum temperature of the pack effectively. However, it is difficult to ensure temperature consistency due to the irregular phase changing [32].

Large current may increase the diffusion induced stress significantly [7], which may cause obvious impact on the battery ageing rate. In addition, the difference in current between batteries can cause temperature inconsistencies between the batteries, thereby aggravating the inconsistencies within the pack. For the batteries connected in parallel where the voltage is same, slight differences may occur due to the resistance on wire and welding points or the position of batteries [33], which can also lead to inconsistency within the pack. For cells in series, their currents are always the same. As mentioned before, the temperature can still be different due to the variety of internal resistance and heat dissipation ability. In addition, the stress on the cells with smaller capacity is higher, leading to faster dropping of capacity. This could form a positive feedback, thereby accelerating the capacity degradation of small-capacity batteries and even resulting in thermal safety risk. Batteries are connected in series and in parallel to meet the system requirements of voltage, power and energy, therefore, the inconsistencies between batteries caused by currents can be significant, especially under harsh conditions such as fast charging, rapid acceleration and uphill driving conditions.

SOC is another important stress factor for battery degradation. High SOC or overcharge means low graphite anode potential, which may result in side reactions (such as the SEI growing), electrolyte decomposition, and higher chance of plating in charging conditions, while low SOC may lead to corrosion of the anode copper current collector and disorder of the cathode material structure [8]. SOC differences between cells can lead to inconsistent aging rates. It is worth mentioning that, inconsistencies between SOCs will cause depth of discharging (DOD) differences in EVs, which will further affect the aging rate of batteries, thereby exacerbating inconsistencies between batteries [34, 35].

2.2 Inconsistency management

The battery inconsistency cannot be completely eliminated, but it can be restricted within a reasonable range [34, 36]. Various method can be applied to improve the battery inconsistency.

The inconsistencies originated from manufacturing process can be attenuated by improving the stability and consistency of raw materials (such as cathode materials, anode materials, electrolyte, etc.) and improving production process uniformity (such as slurry mixing, coating, pole piece thickness, etc.). The uniformity sorting (selecting cells based on criteria such as voltage, internal resistance and capacity) is also effective to ensure an reasonable consistency of the battery pack [28].

After the assembly, the consistency of cells will gradually decrease during the usage process and can develop into serious inconsistency problems if not properly managed. Cell consistency can be improved by appropriate mechanical structure and reasonable TMS design of the pack, while BMS equalization are the most effective means of consistency management [37].

3 Battery thermal management system

TMS can constrain the temperature within a proper range and reduce the temperature gradient within battery pack, thereby improving the inconsistencies between batteries caused by temperature distribution. According to power consumption, TMS can be classified into passive and active systems. Based on heat transfer media, TMS can be roughly divided into air-cooling, liquid cooling, phase change material (PCM) cooling, and direct cooling systems [38, 39].

3.1 Air-cooling systems

Due to the advantages of low cost, simple structure and high reliability, air cooling has become one of the most popular methods of TMS for EV power battery systems. The air-cooling system can be designed in parallel or serial flow layouts to effectively reduce the maximum and average temperature of batteries. However, air cooling systems require a much higher volumetric flow to achieve satisfactory performance because the specific heat capacity of air is significantly smaller than that of liquids [39].

Traditional air-cooling systems are usually based directly on external air without additional pretreatment. In recent years, improvements have been made to air cooling systems to work together with heating ventilation and air conditioning for better performance. Based on the three-dimensional numerical research method, Jilte et.al [40] studied the thermal performance of the air-cooled LIB module, and deeply analyzed the temperature deviation and hot spots. Xie et al. [41] proposed an electrothermal-coupled model to study the thermal characteristics of an air-cooled pack, and verified the simulation results through experiments under various conditions. While it is worthy to denote that large temperature gradient may still occur due to the low specific heat capacity and limited flow strength of air [42].

3.2 Liquid cooling systems

Liquid cooling is an effective thermal management approach for EV batteries. Typical liquid cooling systems include pumps, cooling plates, radiators and other accessories, and water/glycol is the most popular cooling medium. Liquid coolant can be circulated through pipes within the system, and the convective heat transfer between the liquid and the system components is the main cooling mechanism [43]. Yang et al. [44] studied the impact of flow path on a parallel liquid cooling TMS, analyzed the heat dissipation performance under different discharge currents, and proposed an optimization strategy to improve the cooling efficiency for the TMS.

Due to the high heat transfer coefficient of coolants, liquid cooling systems can effectively maintain stable temperatures and reduce temperature gradients, especially under harsh conditions [45] such as uphill or quick acceleration situations, and have been widely adopted by the current commercial electric vehicle market. However, liquid cooling systems usually have the disadvantage of high energy consumption, additional facilities will result in increased costs, and liquid coolants require the system to have a certain degree of corrosion resistance.

3.3 PCM cooling systems

By utilizing the melting latent heat of PCM to absorb heat, the PCM cooling method can be applied to battery TMS [46]. PCM can absorb a large amount of heat without changing the temperature during the phase change, which can maintain temperature uniform between different batteries with in a pack

[32]. In addition, PCMs such as paraffin and expanded graphite have good shape adaptability, so as to fit batteries and modules with various shapes. Lei et.al [47] researched the PCM method and the experimental results illustrated that the maximum deviation of temperature could be 2.6℃. Another experiment carried out by Zhang et.al validated the efficient PCM-based TMS for fast-charging, and the imbalance of temperature could be reduced [48]. Jilte et.al [49] proposed a modified layout method to improve the temperature uniformity of the PCM cooled module, and verified the feasibility of the method at different current rates and ambient temperatures.

The PCM cooling methods are passive approaches using solid-liquid mixed medium as the coolant. In extreme cases, such as persistently high ambient temperature, or the batteries generating heat constantly, the latent heat of the PCMs may be exhausted. At this time, the cooling capacity will be greatly reduced, and it may even bring safety risks. Therefore, hybrid cooling methods that couple liquid cooling and PCM cooling together have been studied to improve thermal management performance [50, 51].

3.4 Direct cooling system

Different from PCM cooling, direct cooling is a kind of active thermal management method relying on the phase change process. Normally, direct cooling TMS consists of pump, expansion valve, cooling plate, compressor, and evaporator. The cooling plate can effectively absorb the heat generated by the batteries through the latent heat of vaporization of the refrigerant. Then refrigerant in the form of a gas-liquid mixture will flow through the compressor and condenser along the pipeline and is fully liquefied. Next, the liquid coolant will flow into the evaporator and expansion valve and be adjusted to the appropriate temperature and dryness. Eventually, the refrigerant will flow into the cooling plate and complete a cycle [38].

The outstanding advantage of the direct cooling system is its high efficiency, which comes from the thermodynamic cycling characteristics. At the same time, direct cooling TMS can effectively reduce the maximum temperature of the batteries and maintain good temperature consistency. However, direct cooling may also bring some inherent problems, such as how to choose a safe, environmentally friendly high-performance refrigerant, and the cost and reliability issues caused by the addition of accessories [42].

3.5 Heating methods

The performance of LIBs, such as discharge capacity and available power, will be significantly affected by low temperatures, in addition, charging at low temperatures can cause unnecessary lithium plating. Therefore, preheating before working at low temperatures is essential to ensure the safety and reliability of LIBs.

External heating, especially thermoelectric-based heating such as positive temperature coefficient (PTC) and electrothermal film (EF), is commonly used for battery preheating [52]. Due to its positive temperature characteristics, the PTC method can maintain a constant temperature range and avoid overheating. However, the PTC method may cause temperature imbalance in the battery pack during heating. The EF is usually made of insulating metal foil, and has the advantages of smaller thickness and better temperature consistency between cells. However, the EF cannot achieve temperature self-control, so there is a risk of overheating.

The external heating can also be integrated with the cooling system in the battery TMS, therefore, media such as air and liquid can be used to preheat the batteries. However, such integration methods will increase the complexity of the system, leading to increased costs and reduced system reliability.

4 Equalization management system

The EMS plays an important role for reducing the inconsistency between the cells in pack. A variety of LIB equalization techniques have been researched, some of which have been implemented in EVs.

4.1 Classifications

EMS can be classified into passive form and active form based on circuit topology. No matter which topology is applied, the battery to be balanced needs to be selected according to specific criteria, which is usually some characteristics of the battery, such as terminal voltage, SOC or capacity. They are also considered as balancing variables. Depending on specific variables, EMS can be classified into voltage-based equalization, capacity-based equalization and SOC-based equalization. According to the balancing control strategy, EMS can be divided into classic control, fuzzy control, model predictive control and other advanced control methods. The typical classification of the equalization technology can be demonstrated in Fig. 2.

As shown in Fig. 3, the passive equalization topologies usually employ a parallel bypass resistor for dissipating excess energy. As shown in Fig. 4-7, the active topologies can transfer energy between cells, modules and packs with the help of non-dissipative structures such as inductors and capacitors. It is confirmed that both active and passive equalization systems are beneficial for slowing battery capacity degradation and extending battery life [53, 54].

EMS is mainly applied in static conditions such as the end of charging, while recently there have been some progress in balancing applications under dynamic conditions i.e., during charging and discharging processes [55, 56]. Shen et al. [57] proposed an active equalization scheme that starts to work after the battery is fully charged or discharged to minimize charge transfer during the balancing process.

4.2 Applications

Passive equalization technology is currently widely used for EVs [58]. Exampling, Tesla, BYD Qin, Roewe ei5 and other EVs have been equipped with passive EMS. Although active equalization technology is only used in a limited range, it has become a hotspot due to its high efficiency and fast speed. Under harsh conditions such as uphill or quick acceleration, the TMS can suppress the temperature rise and improve the temperature consistency, and the equalization technology can effectively improve the battery consistency with the pack to avoid over-discharges happened on worse batteries, thereby avoid fast degradation of batteries.

IC companies such as Infineon and Linear Technology have also introduced chips for battery balancing. For example, the TLE8001 from Infineon can achieve both passive and active equalization functions. LTC6802 [59] and LTC6804 [60] from Linear Technology can achieve active equalization function.

5 Equalization circuit topology

5.1 Passive balancing controller

The passive balancing controllers (PBC) usually employ shunt resistors in parallel with the batteries to dissipate excessive energy of the cells with high voltage or high SOC [61, 62].

As shown in Fig. 3a, the PBC can control dedicated switches (K_1, K_2, …, K_n), typically power semiconductor devices such as MOSFETs, to dissipate energy from the corresponding cells. For instance, assume that Cell1 has higher energy than others, and then switch K_1 is connected to discharge Cell1 thanks to the control signal of Pulse width modulation (PWM). The path of energy transforming is indicated thanks to the blue line. Depending on the equalization control strategy, the switches can work continuously or intermittently, and dissipated energy on the shunt resistor can be estimated by Joule's law:

$$\dot{Q}_{dissipation} = I_{balance}^{2} R \tag{1}$$

where $\dot{Q}_{dissipation}$ is the dissipative power, $I_{balance}$ is the bypass current through the shunt resistor, and R is the resistance of the shunt resistor.

PBC is popular in EVs owing to its simple circuit structure and low-complexity [63]. However, the disadvantages of low balancing efficiency and long equalization time due to low equalization energy and balancing current restricted by heat dissipation conditions in hardware, limit the further application of PBC, especially for large capacity batteries.

Campestrini et al. [64] studied the traditional passive balancing of LIBs using two modules with eight groups serial connected and group of 14 batteries in parallel (8s14p) configuration. Experimental results show that modules with PBC have less than 1% inhomogeneity state for capacity after 1200 equivalent cycles. However, the cell used in this study has a nominal capacity of 2.8 Ah, which is not sufficient to predict the equalization effect of PBC on large-capacity batteries.

To increase the balancing current, Xu et al. [65] developed a special passive balancing topology, in which the shunt resistor is replaced by MOSFET, as shown in Fig.3(b). For instance, assume that $Cell_2$ has higher energy than others, then the MOSFET S_2 works in amplifier mode and other MOSFETs are controlled to be off. The balancing circuit is controllable up to 1.2A (this is why the MOSFET is equivalent to an adjustable resistor in Fig.3.(b).

Amin et al. [66] proposed a passive balancing topology that combines the shunt resistor and MOSFETs. The PBC was applied to a pack consisting of 15 series-connected $LifePO_4$ batteries with a capacity of 200 Ah. However, the balancing process still takes a quite long time compared with operational conditions.

Schmid et al. [67] proposed an equalization topology called electrochemical balancing to passively balance cells without additional electrical devices. Each cell in a string is connected in parallel to a nickel-metal hydride or nickel-zinc cell. LIB cells can achieve equalization by the electrochemical process of the nickel-based cells. Experimental results verify the feasibility of the method. However, the limitation of cost, volume and complexity is very high.

5.2 Active Balancing controller

The active balancing controllers (ABC) have non-dissipative topologies to transfer energy between different cells and modules/packs using various energy buffer devices, including capacitors, transformers, inductors and power converters [68].

The overall advantages of ABCs consist of high efficiency, fast speed and high accuracy. However, compared with PBCs, ABCs have to face the difficulties including complex structure, large size and expensive system cost [69].

5.2.1 Energy transfer path

One of ABC's superior advantages is that the energy can transfer between different levels to achieve system balance, which reduces the energy consumption when achieving the system equalization. Considering the energy transfer path, ABCs can be divided into cell-to-cell (C2C) balancing [70, 71], cell-to-module (C2M) balancing, module-to-cell (M2C) balancing [72] and module-to-module (M2M) balancing. The flexible energy transfer paths are shown in Fig. 4.

As shown in Fig. 4a, C2C equalization denotes that energy can be transferred among batteries in the same module/pack, which is the fundamental mode of ABCs. Phung et al. [73] presented an optimized C2C architecture based on traditional next-to-next balancing topology, which is more compact and easier to implement. Experiments have been performed to prove the availability of the topology. For *n* cells connected in series, the C2C architecture usually needs *n*-1 energy transfer components. Therefore, as the number of cells increases, the circuit will become more complicated.

As shown in Fig. 4b, C2M equalization can transfer energy between the module and internal cell bidirectionally, which has the advantage of impairing the inconsistence between battery modules. Lu et al. [74] proposed an isolated bidirectional C2M controller with zero-voltage switching function. When working in boost mode, the converter can transfer battery energy to the module. The converter can also work in buck mode to transfer module energy to the undercharged cell. Experimental results show that the bidirectional C2M controller has good performance in equalization speed and efficiency.

As shown in Fig.4c, with M2M equalization energy can be transferred between modules. Compared with C2C and C2M, M2M usually has larger size considering the current isolation and more complex strategy to avoiding misbalancing, making implementations more difficult. Ji et al. [75] proposed an equalizer scheme using multiple transformers, by which the energy can be transferred between modules with different voltages, and a 3A equalization current is achieved while the voltage inconsistency is limited to 24 mV.

Other equalization modes have also been studied. Li et al. [76] proposed a module-to-cell-to-module equalization topology. With the help of soft-switching and bidirectional resonant circuit, the equalization speed and efficiency can be effectively improved. Experimental results show that the topology can obtain an efficiency of 93% in C2M mode and 72.5% in M2C mode.

The performance of different equalization paths has been analyzed by researchers. Baronti et al. [77] compared the performance between different energy transferring paths through statistical simulations. Simulation results demonstrate that the C2C topology has the fastest equalization speed and highest equalization efficiency, and the C2M mode has the lowest efficiency. Chen et al. [78] proposed a directed graph method to compute the equalization efficiencies and balancing speed for different topologies. This approach provides a basis for the trade-off between efficiency and speed when choosing the appropriate balance topology. Bruen et al. [78] studied passive equalization mode, C2C mode, and C2M mode respectively and simulated the dynamics current and voltage caused by balancing. The model is versatile and can be used for the auxiliary design of the equalization control system.

5.2.2 Capacitor based balancing controllers

The capacitor based balancing controllers (CBBC) can shuttle energy between cells or between cells, modules and systems [80, 81].

As shown in Fig. 5, CBBCs can be classified into single capacitor topology, switched capacitor topology and multiple-layer capacitor topology [82-84]. It should be mentioned that the CBBC can only transfer energy between batteries with voltage difference.

A typical single capacitor topology is shown in Fig. 5a, which consists of one single capacitor (C), several single-pole single-throw (SPST, K1, K2, …) and single-pole double throw (SPDT, S1, S2, …) switches. The switches can be combined by MOSFETs.

CBBC with single capacitor topology, though with relatively simple control strategy and low energy loss, has a drawback that the balancing time is quite long. During operation, the equalizer screens cells with higher and lower voltages, and then transfer energy between the selected cells by controlling the switches. The process of equalization starts with charging the capacitor by the high-voltage battery and then discharge the capacitor to the low-voltage battery subsequently. For instance, assume that Cell$_1$ and Cell$_2$ are the cells with higher and lower voltages respectively, firstly, SPST switches K$_1$ and K$_2$ are connected and SPDT switches S$_1$ and S$_2$ are connected to the upper side, energy will transfer from Cell1 to the buffer component C as shown by the blue line. Then SPST switches K1 is disconnected, K2 and K3 are connected, SPDT switches S1 and S2 are connected to the lower side, energy will transfer from the buffer component C to Cell2 as shown by the green line.

A typical switched capacitor topology is shown in Fig. 5b, which consists of several capacitors and SPDT switches to transmit energy between contiguous batteries via controlling the switches. CBBCs with switched capacitor topology have similar advantages of simple structure and low cost, but require fine control strategies, especially when there is only a slight voltage difference between adjacent cells. The blue and green lines show the energy transfer path.

Fig. 5c shows a similar double-tiered capacitor topology that transfers energy between adjacent cells through the first-tiered capacitor and transfers energy between batteries not directly connected through the second-tiered capacitors, by which the equalization time can be significantly reduced. The blue line shows the energy transfer path from Cell1 and Cell2 to second-tiered C21, and energy can transfer from C21 to Cell2 and Cell3 to achieve energy transmission between Cell1 and Cell3 shown as the green line. Note that energy must go through Cell2 when balancing Cell1 and Cell3, which will reduce efficiency.

A typical multiple-layer capacitor topology is shown in Fig. 5d. In addition to transferring energy between the cells in the same module, equalization between modules can also be achieved. It should be mentioned that the voltage stress on capacitor C is much higher than the stress on the capacitors inside the modules.

Researchers also proposed other types of capacitor-based topology. For instance, Shang et al. [85, 86] proposed a mesh-structured capacitor equalizer, which can significantly improve the equalization efficiency and speed, as shown in Fig. 6.

5.2.3 Inductor based balancing controllers

The inductor based balancing controllers (IBBC) can shuttle energy between cells or modules through external inductors [87]. Compared with CBBCs, IBBCs typically illustrate faster balancing speed and higher equalization current, however IBBCs are usually more expensive and less efficient [88].

IBBCs can be classified into types such as single inductor topology and switched inductor topology, as shown in Fig. 7 [89, 90].

A typical single inductor topology is shown in Fig. 7a, which includes one single inductor and several MOSFETs with body diodes and can transfer energy between selected cells by controlling the MOSFETs with (PWM) signals. For instance, assume that Cell1 and Cell2 are the cells with higher and lower voltages respectively. MOSFET S1 and S2 are switched on firstly, and the blue line shows the energy transfer path from Cell1 to the buffer component L. The power transferred can be obtained as:

$$\dot{Q} = UI = IL\frac{dI}{dt} \tag{2}$$

where L is the value of inductor L, U and I is the terminal voltage and current of inductor L respectively. Then switch off S1 and switch on S5, energy will transfer from the buffer component L to Cell2 shown as the green line. PWM signals are used to control the MOSFETs to transfer energy between the cells.

A typical multiple inductor topology is shown in Fig. 7b, which consists of several inductors and MOSFETs with body diodes. The energy transferred between batteries is controlled by the MOSFETs. The blue and green line show the energy paths for Cell1 discharge and Cell2 charge respectively. The equalization speed of such topology is affected by the scale of pack, and the speed is usually low because energy can only be transferred between batteries that are adjacent to each other.

A typical resonant inductor topology is shown in Fig. 7c. Resonant circuit is used in place of the single inductor, which can reduce the electromagnetic interference (EMI) emission and decrease switching losses during equalization process. The blue and green line show the energy paths for Cell1 discharge and Cell2 charge respectively.

It is worth mentioning that IBBCs can transfer energy from a cell with lower voltage to the one with higher voltage. Therefore, the balancing strategy should be considered carefully to avoid mis-equalization [91].

5.2.4 Transformer based balancing controllers

The transformer based balancing controllers (TBBC) can shuttle energy between different cells and modules through external transformers. As shown in Fig. 8, TBBC can roughly be divided into single winding transformer topology and multiple windings transformer topology [92-94].

A typical single winding transformer topology is shown in Fig. 8a, which can shuttle energy in M2C mode by controlling the switches. For instance, assume that Cell1 is the cell with lowest energy. Firstly, MOSFET S is switched on and current begin to flow into the transformer from the dotted terminal of the primary sidewinding, and the energy from the module is stored in the transformer. The blue line shows the energy path. Once MOSFET S is switched off, the SPST switches K1 and K2 are connected and the SPDT switches S1 and S2 are connected to the upper side, and the energy held in transformer can be shuttled to Cell1. The green line shows the energy path. More switches and a high voltage transformer are required in TBBC, resulting in high cost and large size.

A typical C2M multiple windings transformer topology is shown in Fig. 8b. For instance, assume that Cell2 is the cell with highest energy. Firstly, MOSFET S2 is switched on and current begin to flow into the transformer from the dotted terminal. Once MOSFET S2 turns off, the energy held in transformer will be transferred into the module. The blue and green lines show the energy paths. This topology is also costly and complex in design [60].

A typical M2C multiple windings transformer topology is shown in Fig. 8c. For example, assume that Cell2 is the battery with the lowest energy. Firstly, MOSFET S is switched on and current begin to flow into the transformer from the dotted terminal. Once MOSFET S turns off, the MOSFET S2 turns on and energy will be transferred into Cell2. PWM signals are used to control the MOSFETs to transfer energy between batteries.

The equalization speed of TBBCs are usually fast, but the voltages of the secondary windings are usually inconsistent due to the uneven leakage inductance of the windings [95]. The fabrication of a transformer with many symmetrical windings for high power applications is another big issue [96].

5.2.5 Power converter based balancing controllers

DC/DC converter, or power converter, can convert a DC source from one voltage to another. Power converter based balancing controllers (PBBCs) have the advantage of high efficiency and accuracy for transforming energy bi-dictionally. PBBC can transfer energy between different cells and modules [97]. The power converter applied in PBBCs can work in buck, boost, and buck-boost mode [98-100], Cuk [101, 102] and other types [103]. Since DC/DC topologies use inductors or transformers as the buffer components, PBBCs have some intersections with IBBCs and TBBCs. PBBCs can achieve high accuracy, but have the evident disadvantage of high cost and complexity.

Buck converter is a DC/DC that steps down voltage from input to output usually with at least two semiconductors and one buffer element. A charging buck-based equalization topology is shown in Fig. 9a [104]. During charging process, each buck circuit can serve as a charger and control the charging circuit individually. Assume that the buck circuit work at continuous conduction mode, the voltage on the battery module can be expressed as:

$$V_{\mathrm{mi}} = V_{\mathrm{ci}} * D_{\mathrm{i}} \tag{3}$$

where V_{mi} is the average voltage on the i^{th} battery module, V_{ci} is the average voltage on the corresponding capacitor, and D_{i} is the duty of the PWM signal. Because each module can be charged separately, it's possible to achieve module equalization in a short time.

Boost converter is a DC/DC that steps up voltage from input to output with at least two semiconductors and one buffer element. A boost-based equalization topology is shown in Fig. 9b [105], which is similar to the charging buck-based equalization topology. The average currents of all the boost circuits are equal, but the average current of each module is different depending on the module voltage and PWM signal duty to achieve module equalization.

Buck-boost converter can implement the functions of buck and boost circuit, and the output voltage can be greater or less than input voltage. A typical buck-boost topology is shown as Fig. 9c, which can transfer energy between adjacent batteries by controlling the switches. For instance, assume that energy should be transferred from Cell2 to Cell1. Firstly, MOSFET S3 is switched on and current begin to flow into the buffer L1. Once MOSFET S3 is switched off, energy will be transferred into Cell1 through the body diode of S1. PWM signals are used to control the MOSFETs to transfer energy between the cells. This bidirectional topology is particularly well suited for balancing applications due to its efficiency and convenience. However, the topology has the shortcomings of high complexity and high cost. Shang et.al [106] introduced the research of circuit based on buck-boost converter and the experimental results are illustrated.

Cuk converter can output voltage greater or less than input voltage with opposite polarity. A C2C Cuk converter topology is shown in Fig. 9d, which contains two inductors and two MOSFET switches. During the equalization process, energy can be shuttled between contiguous batteries with PWM-controlled MOSFETs, and capacitors serves as the main buffer elements for energy transfer. Compared with the buck-boost topology, Cuk circuits have the merits of low ripple current and high efficiency, however, the Cuk circuit contains more components and is therefore more expensive. Moghaddam et al. [107] proposed a special Cuk converter circuit to reduce the number of components. This solution uses n switches for n cells instead of the traditional 2n-1 switches, so it is more competitive.

The flyback converter is a type of isolated DC-DC, and can output voltage either greater or less than the input voltage. Flyback-based equalization topology has been applied in the fields of EVs [101, 108]. Lin et al. [109] proposed a bidirectional flyback-based topology, which can transfer energy between the battery and buffer capacitor. Experimental results of $LiFePO_4$ battery modules show the feasibility of the M2M approach. Chen et al. [110] proposed a C2C equalization topology based on flyback and forward operation, which can shuttle energy between batteries directly. Therefore, the topology has good equalization efficiency and speed.

5.2.6 Other topologies Controllers

Other functional topologies have also been explored for battery balancing [111, 112].

To improve balancing speed, Altemose et al. [113] proposed an autonomous floating voltage balancing topology, which corporates “share bus” with DC/AC converters to achieve cell balancing. The bidirectional DC/AC converters utilize a phase locked loop ASIC. Liu et al. [114] improved the equalization circuit by using planar transformer as the energy carrier to improve the consistency and reduce volume. The share bus based topology is shown in Fig. 10, Fig. 10a shows the equalization topology, and Fig. 10b shows the details of the DC/AC converter.

Peng et al. proposed a multi-levels balancing topology based on the buck-boost converters to minimize the circulating loss during equalization process. The multi-levels topology is shown in Fig. 11, which can significantly reduce the switching loss with zero voltage switching technique, and improve balancing speed due to flexible equalization paths such as C2C and M2M.

5.3 Hybrid Balancing topologies

Hybrid topologies can improve the balancing performance thanks to the combination of passive equalization and active equalization. Fang et al. [115] proposed a hybrid balancing topology based on DC/DC and shunt resistors. DC/DC can transfer energy from module to charge the battery with lower voltage, and batteries with higher voltage can be discharged by shunt resistors in parallel.

Zhang et al. [116] proposed a hierarchical balancing topology to improve the equalization performance of series-connected cells, which is shown in Fig. 12. The topology includes two balancing layers. The top layer delivers energy between modules based on multiple windings transformer, and the bottom layer applies buck-boost converter to shuttle energy between contiguous batteries in the same module. Experimental results show that the hierarchical topology can significantly reduce the energy loss and balancing time during equalization process.

5.4 Summary of Equalization Topology

The topology is the foundation of equalization system which determines the cost and size of the entire system. An effective topology is essential to extend the lifespan and improve battery performance effectively. It is crucial to select the appropriate equalization topology according to system requirements.

The passive topology has the advantages of uncomplicated circuit, low price and convenient to implement, therefore, it has been widely adopted by EVs such as Tesla and BYD. However, passive topology usually has low balancing speed, and the dissipated power will reduce system efficiency and may even cause thermal runaway risk to the batteries [117].

The active topology is popular for good efficiency and relative low power loss. Compared with passive equalization, active topology can effectively reduce the inconsistency between cell capacity and internal resistance, and improve battery lifetime and available energy [118].

Among the AEM topologies, CBBCs has the merits of low price and simple strategy, while the equalization time required is quite long. IBBCs can transfer energy bidirectionally and have moderate balancing speed, but have the disadvantages of EMI problem and complex equalization strategy. TBBCs have high equalization current and high efficiency, but the manufacture of transformers with symmetrical windings is quite difficult. PBBCs such as buck-boost converters and Cuk converters have attracted much attention due to their high balancing efficiency and easy integration, but the cost and the complex control strategy are their shortcomings[119]. New topologies such as hierarchical structure can reduce equalization loss and balancing times, but still require more verification.

Since passive and active equalization topologies have distinctive characteristics, they can be applied in different scenarios according to the requirements, such as applying passive topologies to HEV and applying active topologies to pure EV or PHEV [120].

Table 1 summarizes the advantages and disadvantages of the current balancing topologies and Fig. 13 shows a result of comparison [88, 90, 121, 122][122][122]. It is worthy to denote that the criterion for classification are based on quoted references and the applicational experience. Therefore, some special design or technical upgrade may differ from this content.

6 Equalization strategies

Equalization strategies are used to control the operation of the equalization systems and can greatly affect the balancing effect. Inappropriate equalization strategies can lead to misbalance or overbalance issues, result in unnecessary power loss and battery decay, and even cause thermal safety risks. Various researches for equalization strategies are carried out to explore[123][123]. Equalization variables and equalization control algorithms are the main contents of the equalization strategies, and the overall profile is summarized in Fig. 14.

6.1 Equalization variables

The equalization variables are the basis for the equalization strategies. The sample accuracy, computational cost and potential hysteresis character should all be comprehensively considered when choosing the equalization variables. Several variables have been used for equalization, including voltage, SOC, capacity, where voltage and SOC are the most commonly used thanks to the easier estimation approach. The characteristic of the equalization variable is shown in Table 2.

6.1.1 Voltage-based equalization strategy (VBES)

VBESs use the terminal voltage collected by BMS as the basis for selecting batteries to be balanced. The terminal voltage can be measured directly with a satisfying accuracy, therefore, VBESs become the most classical and feasible methods. In Atrin's design [124], only one voltage sensor could be used per two batteries. Yang et.al [125] presented a rigorous analysis and design of VBESs. With the help of symmetrical voltage multiplier, the voltage of series-connected cells with different initial conditions can be balanced. However, the nonlinear polarization effects of LIBs may cover up the open circuit voltage (OCV) of LIBs resembling the real capacity, which may cause problems such as mis-equalization or over-equalization.

To improve the performance of VBES, an OCV-based equalization strategy (OBES) is proposed to be a substitute for VBES. However, the online measurement of OCV is still difficult unless with sufficient rest time which is rarely achieved. Meng et al. [126] studied the fast estimation method of OCV based on time delay, which can achieve higher estimation accuracy with shorter rest time. VBESs or OBESs, implemented with the measurement of temperature and current, can help extend the pack lifespan and reduce safety risks in BMS [127-129].

Because the internal resistance could cause a voltage drop when current is applied, the voltage difference may be greatly affected across the equivalent series resistance. Therefore, VBESs and OBESs may not work properly when the vehicle is driving [130]. Generally, VBESs and OBESs are often used for the equalization of ternary LIBs with a relatively linear OCV-SOC curve, but they may be not effective and increase the risk of mis-balance when applied to $LiFePO_4$ batteries [131]. Another state-of-art researches are carried out to improve the OBES. Song et.al introduced a methodology based on charging voltage curve, which can achieve high precision with low computation cost. The strategy was embedded in a BMS system and the experimental results verified the applicability and accuracy.

6.1.2 capacity-based equalization strategy (CBES)

CBES can be used to balance the actual capacity of the battery. However, the actual capacity of the batteries will be influenced by conditions such as current and temperature, so it is difficult to identify the actual capacity and ensure the uniformity of the battery capacity [24].

Ma et al. [132] analyzed the battery pack equalization criterion based on capacity utilization, and proposed an online active equalization strategy for capacity maximization. Testing based on a module with 4P16S LIBs was performed to verify the feasibility and reliability of the online equalization strategy. Cui et al. [133] developed a balancing strategy based on chargeable and dischargeable capacities to tackle the non-uniformity issue in the battery pack. Consistency simulation illustrates that the performance of CBES is better than VBES, which can increase the available pack capacity during charging and discharging. Wang et al. [134] introduced an active balancing strategy based on the residual capacity of the cells, and the experimental results prove the feasibility of the proposed equalization strategy in EVs.

6.1.3 SOC-based equalization strategy (SBES)

SOC is the popular variables to characterize the remaining capacity. Investigations show that SOC-based equalization can be more robust than the voltage-based equalization under dynamic conditions [64, 135]. However, similar to capacity, SOC cannot be measured directly and has to rely on online or offline estimation methods.

Various methods have been researched for precise and robust SOC estimation including directly estimation or model-based method. The coulomb count (CC) method is a popular open-loop approach to calculate battery SOC directly by accumulating the current. Though CC method has the advantages of low complexity, it is less robust when dealing with initial SOC offset and accumulated current measurement errors [64, 135].

The model-based methods can be classified as physical models and data-driven methods [137]. The former one refers to the methods based on the battery physical models, including the electrochemical models (EMs), the equivalent circuit models (ECMs), etc. Generally, EM could be established based on the electrochemical reaction of the battery, where the widely promoted EMs consist of the pseudo two-dimensional (P2D) model [138] and single particle model (SPM) [139]. Due to the complexity of the algorithm, it is almost impossible to use P2D online. SPM may not be able to handle high current rates applications, which limits the application in embedded system of EVs [140]. ECM could well represent battery dynamic characteristics, and is widely applied in online SOC estimation due to the low computational cost (the first-order ECM contains only three parameters). The filtering algorithm are widely used in ECM methods, including Kalman filter (KF) series, information filter (IF), particle filtering (PF) and others [141, 142]. The KF family methods are commonly used due to the moderate calculation cost and high precision, and have satisfying abilities to correct errors. Table 3 shows the comparison between different SOC estimation methods.

Table 3 Comparison of SOC Estimation Methods

Name	Characteristic	Complexity	Accuracy	Merits	Demerits
KF [143]	recursive estimation, dynamic error bounds	medium	low (about 5%)	moderate complexity	low accuracy in highly nonlinear applications
EKF [144-146]	linearization based on first-order Taylor series expansion	medium-high	medium (about 3-4%)	handle nonlinear time varying system	first-order accuracy, accuracy depends on prior knowledge
UKF [147, 148]	unscented transform replaces Jacobi matrix in EKF	medium	medium (about 3%)	UT based on statistical method improve accuracy	high measurement noise may cause divergence
CKF [149]	cubature rule from Cartesian to radial.	medium	high (<3%)	High computational efficiency and stability	inaccurate model error and noise may lead to large error
PF [150]	Monte Carlo method based on importance sampling	high	high (about 2-3%)	not constrained by the linear model and Gaussian noise assumptions	huge computational cost

Thanks for the development of information technology, a large amount of high-quality data covering various working conditions can be obtained, which makes it possible to develop data-driven SOC estimation methods [151]. Chen et al. [152] designed a feedforward neural network (NN) model to achieve high accurate SOC estimation. Experimental results demonstrate that the method can converge at erroneous initial SOC value and can reach an estimation error within 2%. Awadallah et al. [153] presented an accurate SOC estimation technique using neuro-fuzzy inference systems method. Laboratory experiments were performed on a 5.3 kWh battery module and the experimental results demonstrate the proposed method has better accuracy than traditional CC method. Sergio et.al [154] introduced an equalization method based on SOC estimation, and the results under different initial SOC and different battery capacities proved the feasibility of the method.

Factors including temperature and degradation can affect the precision of SOC estimation significantly. Wijewardana et al. [155] proposed a new dynamic battery model considering heat generation mechanism and the ambient temperature effect. Simulation and experimental results show that the maximum error of SOC estimation could be reduced to 2%. Battery capacity will gradually decrease with degradation, therefore the SOC estimation may encounter the issue of large deviation without considering the aging effects. The joint estimation methods can improve such problems [153, 156-158], but the practicality needs further verification. Hua et al. [58] offered a coupling SOC and state of health (SOH) estimation framework based on nonlinear predictive filter. The experimental results indicate that the SOC estimation results have better accuracy than the nominal method. Wassiliadis et al. [159] analyzed the SOC and SOH estimation approach using dual extended Kalman filter (DEKF) and verified the ability to improve the accuracy of SOC estimation over battery lifetime.

Complex methods can obtain high SOC estimation results [15, 160], but may result in high computational cost. Therefore, it is important to maintain a balance between estimation accuracy and model complexity. Xu et al. [161] proposed a PI observer-based SOC estimation method with low computation cost, and introduced an SOC-based equalization approach to improve efficiency and reduce calculation time. Simulation and experiments were performed to verify the strategy with UDDS current profile. Zhang et al. [162] presented a method based on static SOC and influencing factors such as temperature, current and SOH, and designed an equalization technique based on genetic algorithm to plan energy and equalization time. Test results show that the technique can effectively save energy and time.

Considering the application in EVs, the SOC estimation of battery pack or modules may be more suitable. Another possible way to improve the performance of equalization is to identify batteries that need to be balanced, which can be associated with classification methods including supporting vector machine and clustering.

6.1.4 Hybrid methods based equalization strategy (HBES)

HBESs are also developed to take advantage of different equalization strategies [163]. Zhang et al. [164] designed a hybrid equalization algorithm based on SOC and voltage, and adopted corresponding strategies within different voltage ranges. Simulation results show that this hybrid strategy is more effective than SBES. Wu et al. [165] proposed a voltage-SOC equalization strategy, which can estimate the SOC difference indirectly based on voltage and pack SOC. Experimental results verified the performance of the control scheme. Xu et al. [131] proposed a three modes hybrid equalization strategy to accelerate the balancing procedure. The simulation results showed that such hybrid strategy can accelerate the equalization procedure with same hardware.

Considering the relationship between inconsistency and battery degradation, SOC and SOH can be combined to achieve better balance performance. Ren et al. presented a hybrid equalization method based on coupling estimation methods. SOC can be estimated based on EKF method, while SOH can be obtained by a second-order polynomial with parameters including SOC, temperature, current, and DOD. Simulation results demonstrate that active balancing method can effectively improve SOC imbalance between cells.

6.1.5 Other equalization variables

Recently, lots of research has been taken on equalization variables other than voltage, capacitance, and SOC, and the control algorithms based on these variables have been studied.

Diao et al. [24] proposed a novel balancing method based on the residual available energy and validate the effectiveness of the method through experimental results. The equalization scheme emphasizes available energy rather than equalization speed.

Wang et al. [166] developed a state-of-balance (SOB) based strategy that considered battery voltage, terminal pack voltage, current and temperature as the state characterization. The balancing method is made based on the comprehensive imbalance assessment obtained from UKF algorithm. The accuracy and adaptability of the strategy is verified by a 12-string 60Ah NMC LIB pack. Electrochemical models can also be used to evaluate the inconsistency of the pack [167].

6.1.6 Summarization of balancing control variables

The selection of equalization variables is the crucial part in the equalization process. VBESs are the most feasible balancing methods because of the advantages of convenient measurement and high accuracy. However, the battery polarization and voltage sample error may cause mis-equalization problems. CBESs and SBESs are also widely used options. But the battery capacity and SOC estimation faces the contradiction between precision and computational cost. Therefore, HBESs such as the hybrid equalization algorithm based on SOC and voltage or other variables can be used to combine the advantages of different control variables.

In addition to balancing strategy based on voltage, capacity and SOC, balancing strategy based on variables such as available energy and SOB are also researched. The feasibility and accuracy of these methods require more validation in the simulation platform and the actual BMS.

6.2 Equalization Control algorithms

The equalization control algorithms are also crucial for the equalization performance, which used for determining the current and balancing time. Generally, the equalization control algorithms can be roughly divided into classic control algorithms (CCA) and advanced control algorithms (ACA). These algorithms may be feasible in some specific cases and should be selected based on comprehensive considerations such as computational cost, sampling interval, and robustness.

6.2.1 Classic control algorithms

CCAs perform classic mathematical operations based on selected equalization variables. Normally, CCAs utilize the result of classic arithmetic operations such as extremes, averages, standard deviations and variances as the equalization criterions. Due to the advantages of calculation flexibility and high applicability, CCAs have been widely adopted in EV applications in recent decades.

Extreme value equalization algorithms (EVEAs) apply the extremes of equalization variable as the balancing objective. EVEAs are basic and effective strategies with limited computational cost, but often have the issues of misbalance due to the unreliable robustness. Shu et al. [168] presented an extreme voltage balancing algorithm using auxiliary one-inductor balancing circuit, which can help transfer energy from the capacitor with the highest voltage to the one with the lowest voltage. Liu et al. [169] designed an active equalizer where the battery with highest SOC could transfer energy to the cell with lowest SOC during discharging process. EVEAs work well when the cells in the pack differ greatly in the selected variables, otherwise they can cause over-equalization and may even degrade the battery pack performance [78].

Average value equalization algorithms (AVEAs) calculate the average of the selected equalization variables and then use the average value as the criterion for performing the balancing logic. Wang et al. [132] proposed an equalization algorithm that can transfer energy from the most charged battery to the pack until reaching the upper bound of the average SOC, and then transfer energy form the pack to the weak batteries. AVEAs are widely used in EV applications due to its simplicity and reliability. The equalization efficiency and balancing time may be affected by the selected variables, which should be carefully considered based on specific conditions.

6.2.2 Advanced control algorithms

Many advanced control methods such as model predictive control (MPC) and fuzzy control (FC) have been applied to the equalization applications [166, 170-172].

MPC is a kind of advanced control theory which uses rolling real-time optimization to predict dynamic changes and adjust stepwise-optimal control based on established models to achieve optimal performance [173]. Compared with the optimization algorithms, MPC has less computation cost and has been widely used for nonlinear systems control [174-176]. MPC method could deal with the internal polarization problem based on the established battery model, which could predict the battery state to predict or offset the polarization. Altai et al. [177] presented a MPC algorithm applying orthogonal decomposition to achieve SOC and thermal balancing using limited predictive information. Simulation results of modular batteries show promising performance for real-time implementation. Song et al. [178] introduced an MPC-based equalization method and verified the rationality through a testbench. Experimental results show a 31% time reduction compared with common control method. Zheng et al. [179] proposed an MPC-based balancing strategy for aged LIB packs. Compared with classic average SOC strategy, the MPC-based strategy can converge the SOCs and voltages to a more uniform level and effectively avoid over-equalization. Liu et al. [180] proposed a nonlinear MPC architecture to achieve C2C equalization within a pack, which helps to solve the multi-objective balance between SOC imbalance and energy dissipation during the balancing process. Simulation results verify the feasibility of the strategy.

The fuzzy control is another advanced control theory which processes imprecise information relying on degree of membership and fuzzy principles from expert knowledge [181, 182]. Jia et al. [183] introduced a fuzzy controller which regarded the non-equalization degree and the load current as the inputs. Simulation results show that the fuzzy control algorithm has strong robustness and can stabilize the balancing control system in a short time. Ma et al. [184] proposed a fuzzy logic based approach that uses SOC and temperature difference as fuzzy inputs to protect the pack from SOC and thermal imbalances. Cui et al. [185] proposed a multi-switched balancing system based on fuzzy control algorithm for LIB packs in EVs. Experimental results for $LiFePO_4$ and lithium nickel cobalt aluminum oxide batteries showed that the fuzzy control approach can effectively reduce the equalization time and improve the pack capacity. Zhang et al. [186] presented a self-learning fuzzy logic control approach to regulate the equalization period based on the cell voltage deviation. Experimental results show that, compared with the traditional method, the approach can shorten the equalization time by 27% and reduce the cycles by 59%.

More advanced control algorithms, including neural network [187, 188], PID approach [189] and coupled algorithms [182], are also considered to have the potential to improve the equalization performance. Bouchhima et al. [191] proposed a network optimization method to improve the balancing efficiency. The equalization requirement is considered as a nonlinear optimization issue, and can be solved with network modeling and dynamic programming. Simulation results show excellent improvement in efficiency and robustness against the interference. Nguyen et al. [192] employed an adaptive neural fuzzy network approach combined by fuzzy logic and NN methods to tune the membership functions, which is shown in Fig. 15. The equalization system was implemented on hardware, and the experimental results prove the good adaptability and dynamic performance.

6.2.3 Summarization of balancing algorithms

CCAs such as EVEAs and AVEAs have been the primary equalization approaches in EV applications due to the advantages of simple structure and low complexity. However, CCAs may cause mis-equalization or over-balance because of the factors such as noise interference and sampling error associated with limited computational cost for embedded system in EVs.

In addition to CCAs, ACAs is also widely used in balanced applications. MPC approach, fuzzy control approach and PID approach are parts of ACAs, which have great convergence, stability and robustness, and can effectively improve the issues of over-balance and mis-balance. However, the high complexity of the algorithms results in higher computational cost, and the control performance depends on the high-precision model, which is difficult to obtain. With the gradual improvement of multi-core microcontroller performance, ACAs may play a more important role in future battery equalization systems.

7 Future discussion

Future research directions for automotive lithium-ion battery equalization systems may include:

- **Optimization of equalization circuit topology.**

  The fact, that the non-dissipative topology has the superior performance both for efficiency and speed, is the main cause for the promotion of active equalization. However, the conflicts between requirements such as cost, size, complexity, reliability and modularity limit the application of non-dissipative topologies. Therefore, more improvements are needed for high reliability, low cost, and highly integrated dedicated ICs. Besides, the specific topology may be more feasible for the various application such as electric bus and other commercial EVs.

- **Appropriate equalization variables coupled with control strategy.**

Traditional equalization variables such as voltage have been widely applied, which may cause problems of mis-equalization or over-equalization. The SOC-based strategy has also become a research focus, but the SOC estimation accuracy and robustness limit its development. With the in-depth study of the degradation mechanism of LIBs, the multi-variables based strategy will become the future trend. CCAs are the primary balancing method in EVs but their performance may be greatly affected by factors such as noise interference. ACAs have good convergence, stability and robustness, but the computational cost is high. More experiments based on operational conditions need to be carried out for the preferred control strategy with appropriate variables.

- **Coupling more system for improvement.**

  Thermal management systems can be applied to maintain temperature consistency within the battery pack/module, which can effectively reduce the inconsistencies of cells during usage. Equalization method can help reduce the pack imbalance and avoid problems such as overcharging or over discharging. The combination of TMS and EMS can further improve the uniformity of the batteries, thereby improving the service life and safety.

- **Innovation of cloud control.**

  The frequent equalization is less necessary due to the slowly change of inconsistency thanks to the update of advanced battery technology. Therefore, the cloud control based on the cloud database is the feasible method to predict the inconsistency evolution and search for the best control solution with the help of machine learning or deep learning method. Benefit from the innovation of intelligent technology, the cloud control method can be applied to accurate estimation based on complex battery models on the cloud, and then a better optimization strategy can be realized for equalization. Although the application of cloud control is still on studying, with the gradual improvement of control method based on cloud computing, the cloud control equalization may become the future trend.

8 Conclusion

LIBs have been extensively used in EVs due to their pleasuring performance. However, the battery imbalance deteriorated with the aging effect can lead to gradually degradation of performance and even the risk of thermal runaway. Battery equalization technology is critical to improve the cell safety and performance. In this work, the commonly used types for equalization system in EVs, including topologies and control strategies, are reviewed.

Based on the circuit topology, equalization systems can be classified into passive and active topologies. The most recent studies in equalization topology existing literature and applications are thoroughly reviewed. The passive topologies are widely used in EV applications owning to their low cost and ease of implement. However, the power dissipated by bypass resistors will reduce system efficiency and can lead to thermal problems. Compared with the passive topologies, the active topologies have the advantages of high equalization efficiency and high speed, which can effectively improve the consistency of pack but with high cost and complex control strategy as extended burden.

As for equalization control strategy, which is commonly based on terminal voltage and state of charge, more mathematical methods including model-predict-control and fuzzy control are introduced and analyzed in depth. The concern of strategy is concentrated in the optimal selection of control variables and innovation of control algorithm. Despite some breakthroughs in theoretical research and practical applications in recent years, it is still difficult for EMS to meet the comprehensive requirements of accuracy, speed, efficiency, complexity and cost. Therefore, research directions for automotive lithium-ion battery equalization systems such as cloud control method and hybrid equalization system equipped with thermal management system are expected in the future.

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Table 1 Comparison between different topologies

Balancing topologies		**Time**	**Structure complexity**	**Control difficulty**	**Efficiency**	**Volume**	**Cost**
passive equalization		2	5	5	1	5	5
CBBC	switched capacitor	2	4	4	4	4	4
	double-tiered capacitor	3	3	3	4	3	4
	multiple-layer capacitor	3	2	2	4	3	3
IBBC	multiple inductors	4	3	3	3	3	2
TBBC	multiple windings transformer	4	2	3	3	2	2
PBBC	Cuk	4	2	2	4	3	2
	Buck-Boost	4	2	2	4	3	2

Note: the classification is divided into 1-5. 1 means the worst performance, 5 means the best performance, and others refer to moderate ones.

Table 2 Performance comparisons for each of the equalization variables

Equalization Variables	**Voltage**	**Capacity**	**SOC**	**Hybrid**
Merits	easy to sample with high accuracy, simple control logic	accurately reflect the inconsistency of system	accurately reflect the inconsistency of system	high precision and high efficiency
Demerits	affected by voltage platform and polarization effect	cannot measure directly online, high computational cost	contradiction between precision and computational complexity	High computational cost and complex control logic

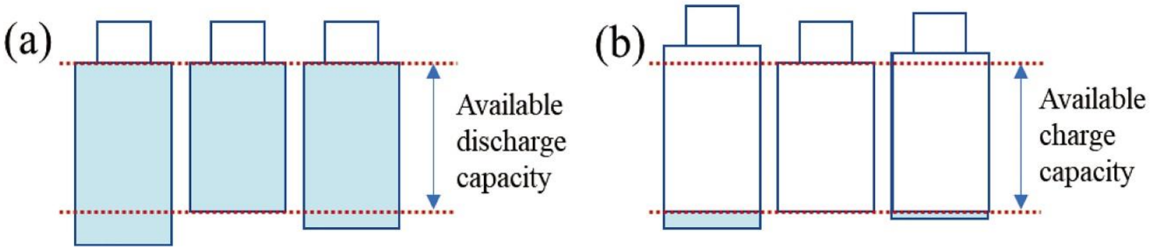

Fig. 1. Impacts of cell inconsistencies of battery pack. (a) available discharge capacity. (b)available charge capacity.

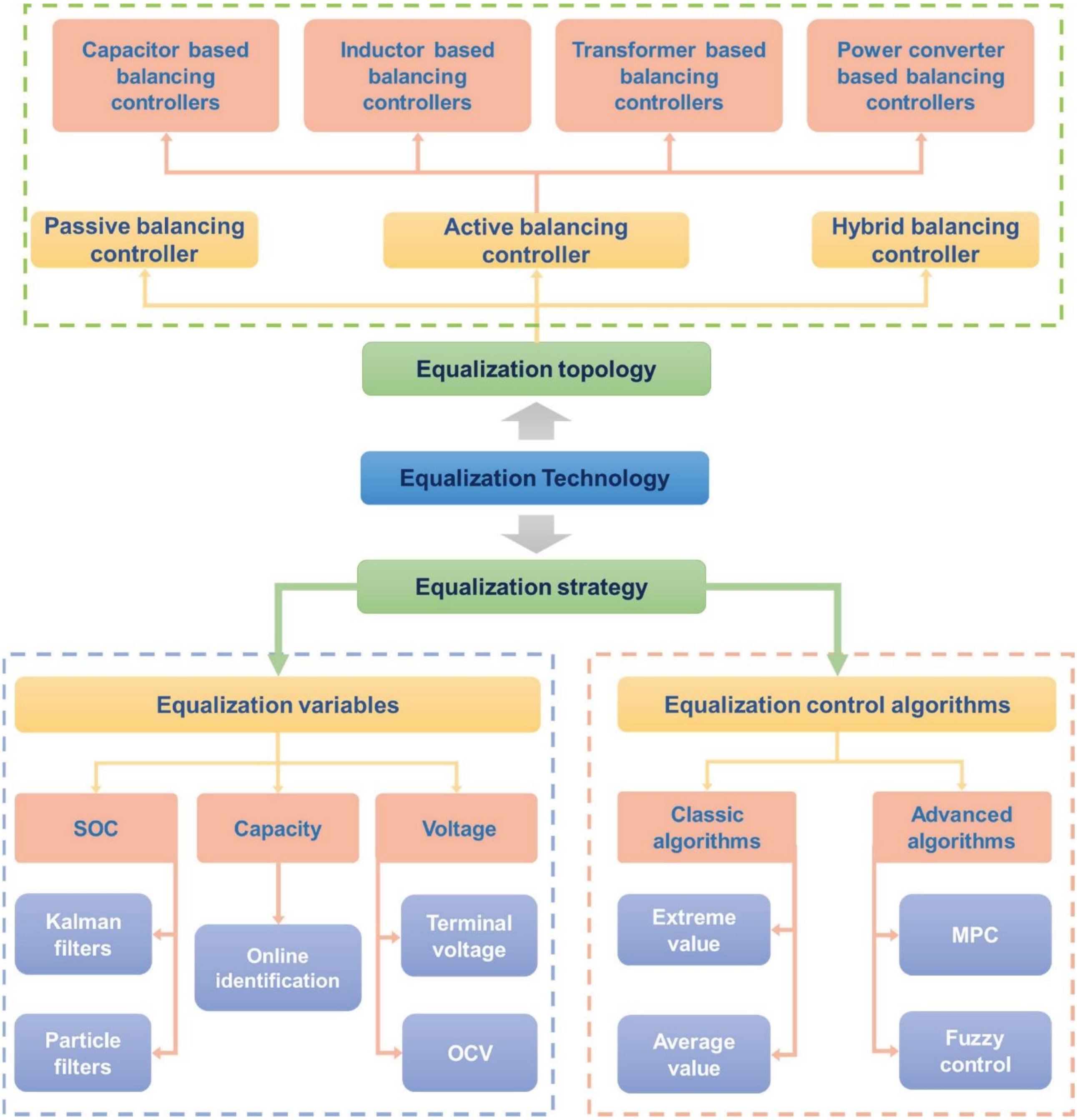

Fig. 2. The general classification of the equalization technology.

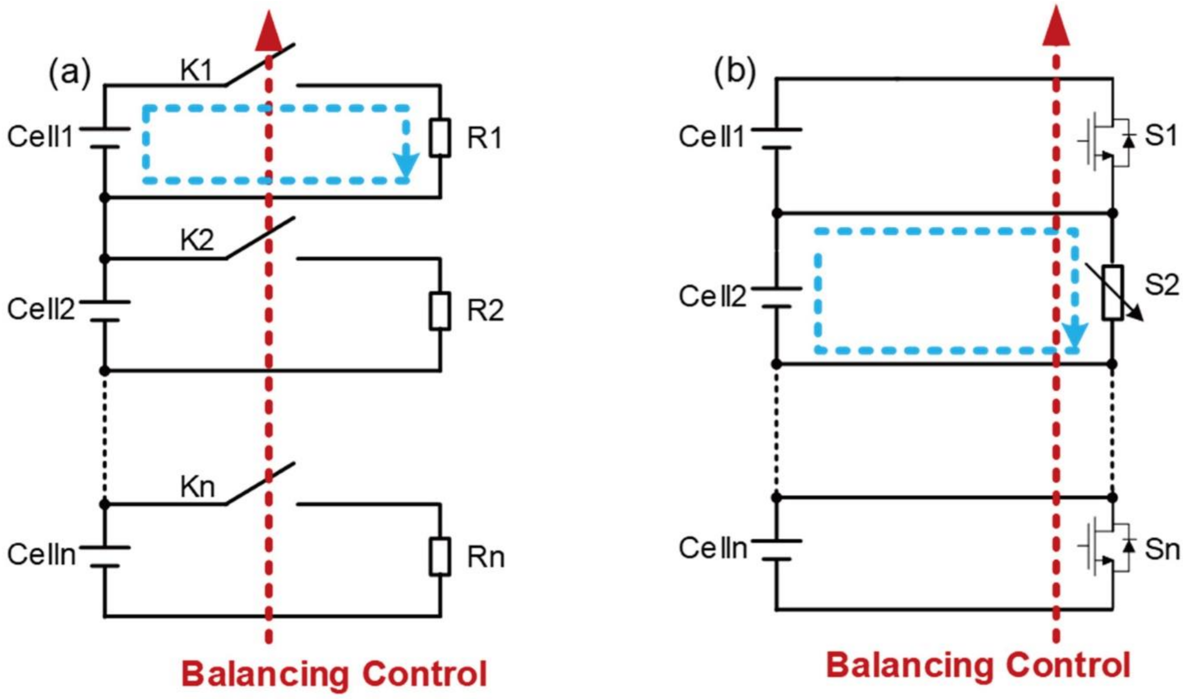

Fig. 3. Circuit of passive balancing topology. (a) Traditional resistor mode with low balancing current. (b) MOSFET amplifier mode which can support high balancing current.

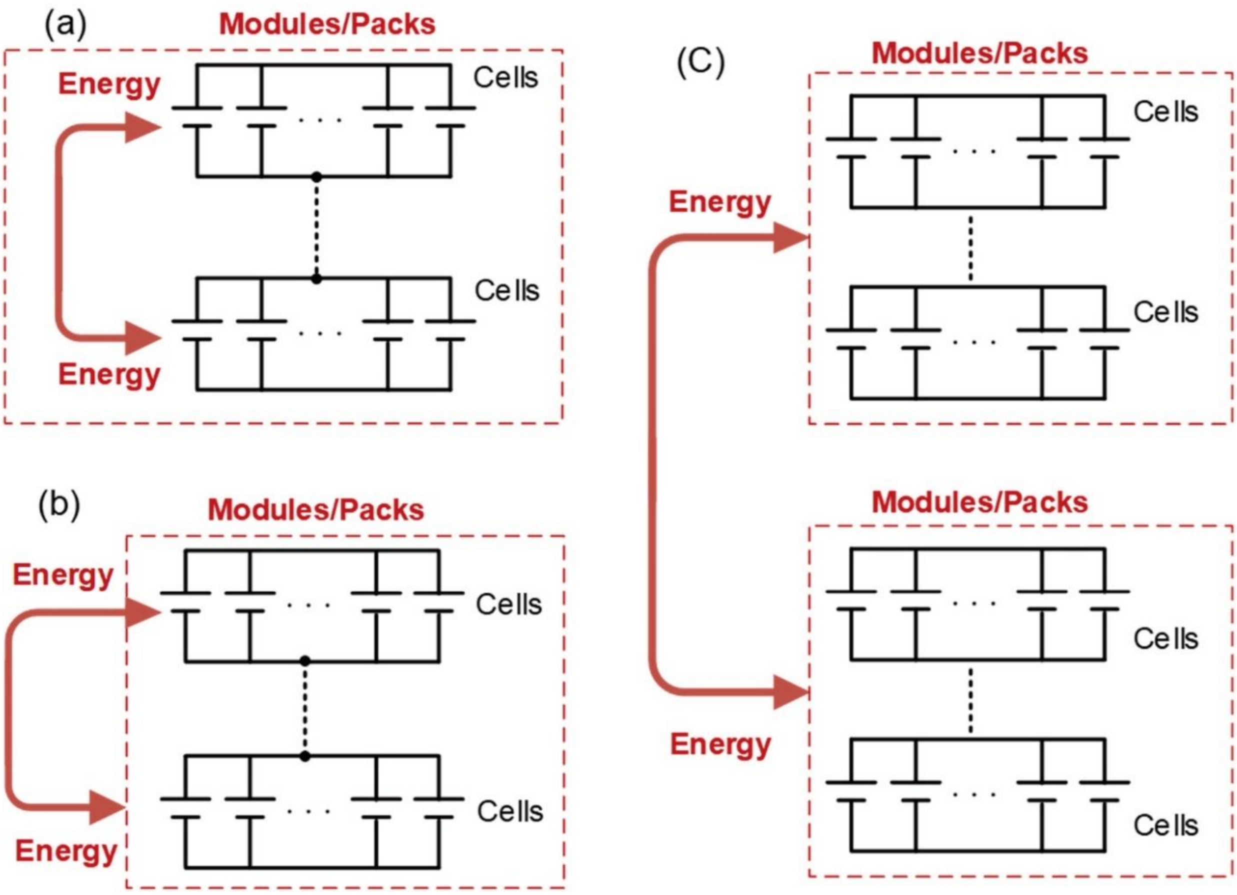

Fig. 4. Different energy transfer path. (a) Cell-to-cell (C2C). (b) Cell-to-module (C2M) or module-to-cell (M2C). (c) Module-to-module (M2M) balancing mode.

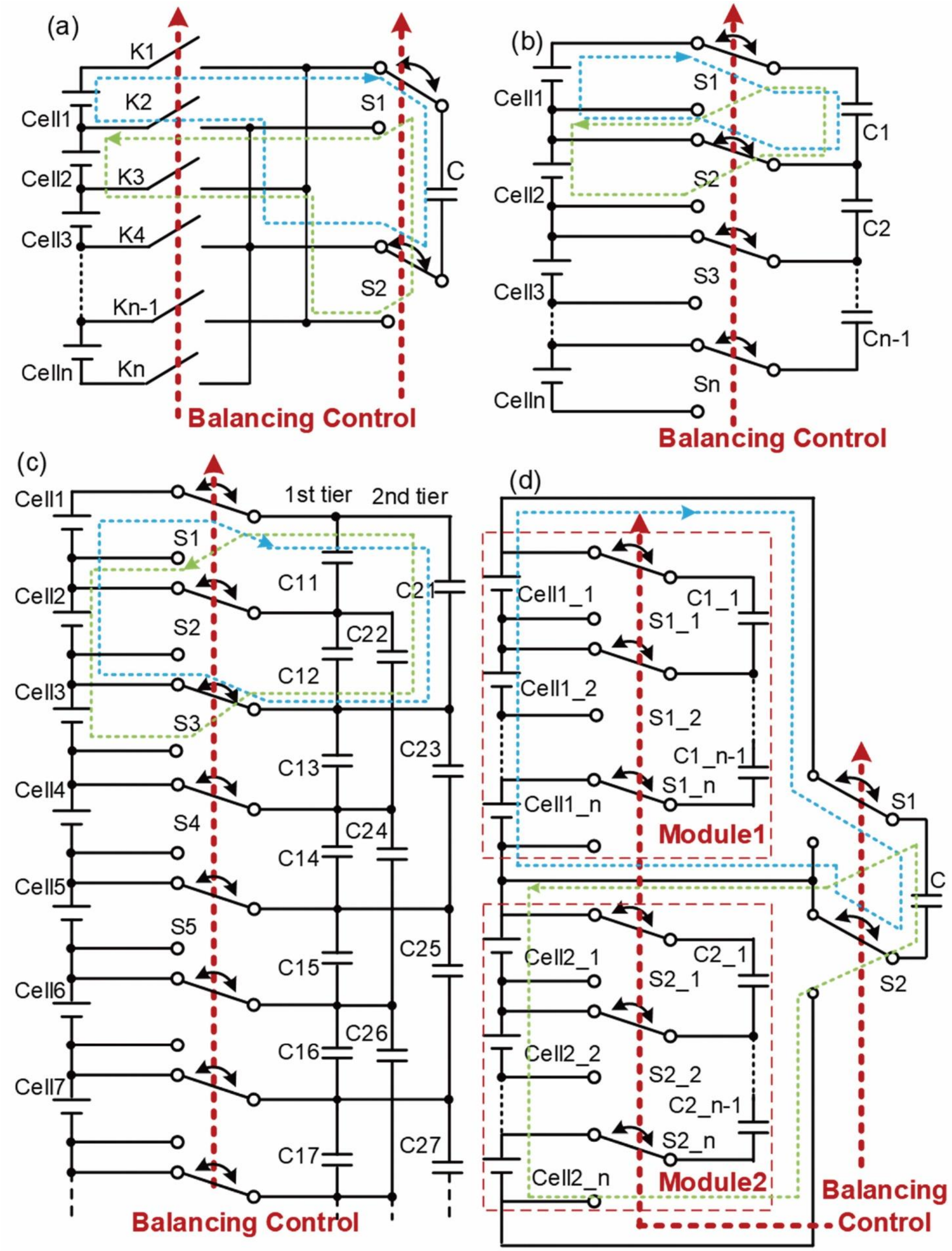

Fig. 5. Capacitor based balancing topologies. (a) C2C single capacitor topology. (b) C2C switched capacitor topology. (c) C2C double-tiered capacitor topology. (d) Multiple-layer capacitor topology.

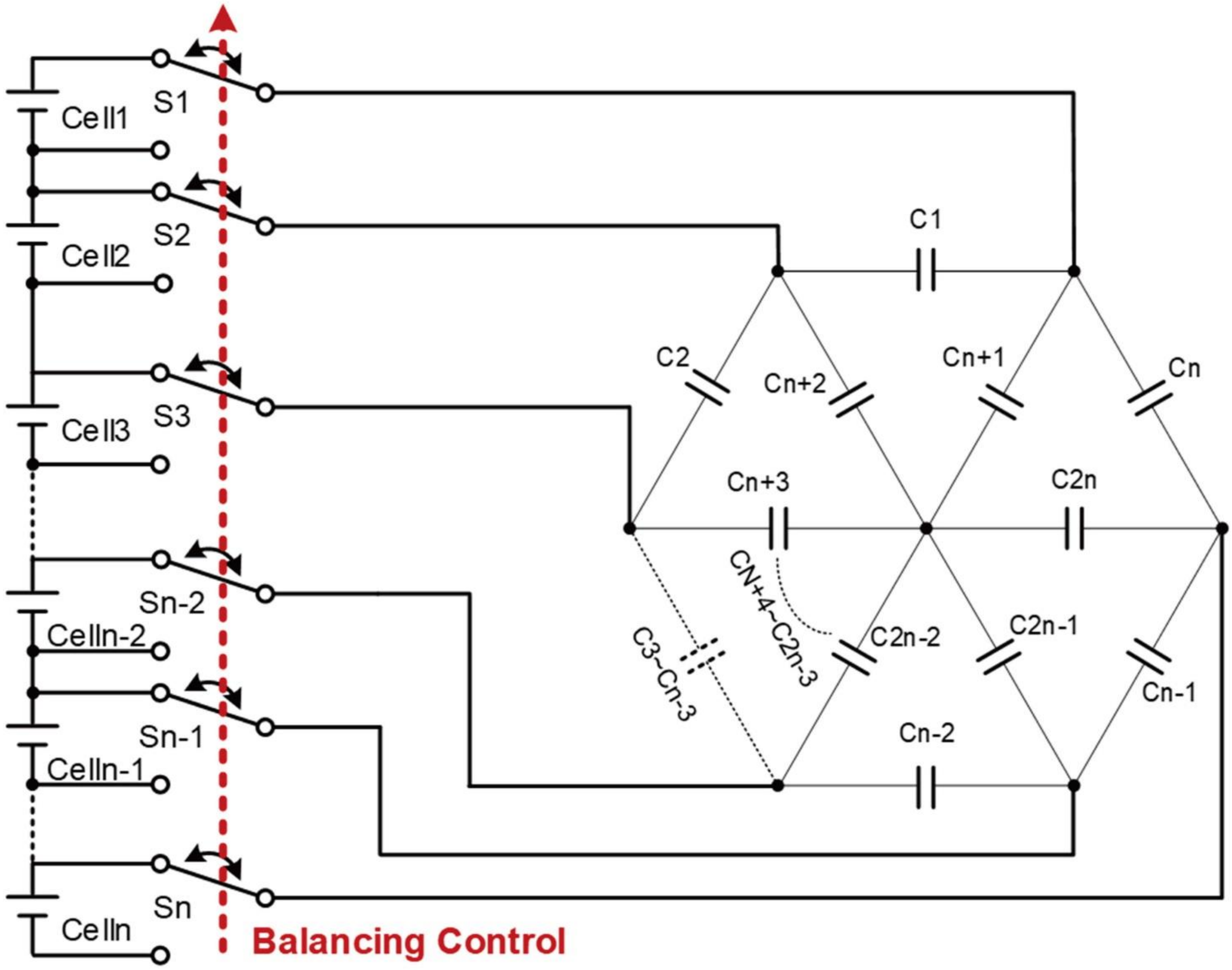

Fig. 6. Topology of mesh-structured capacitor equalizer.

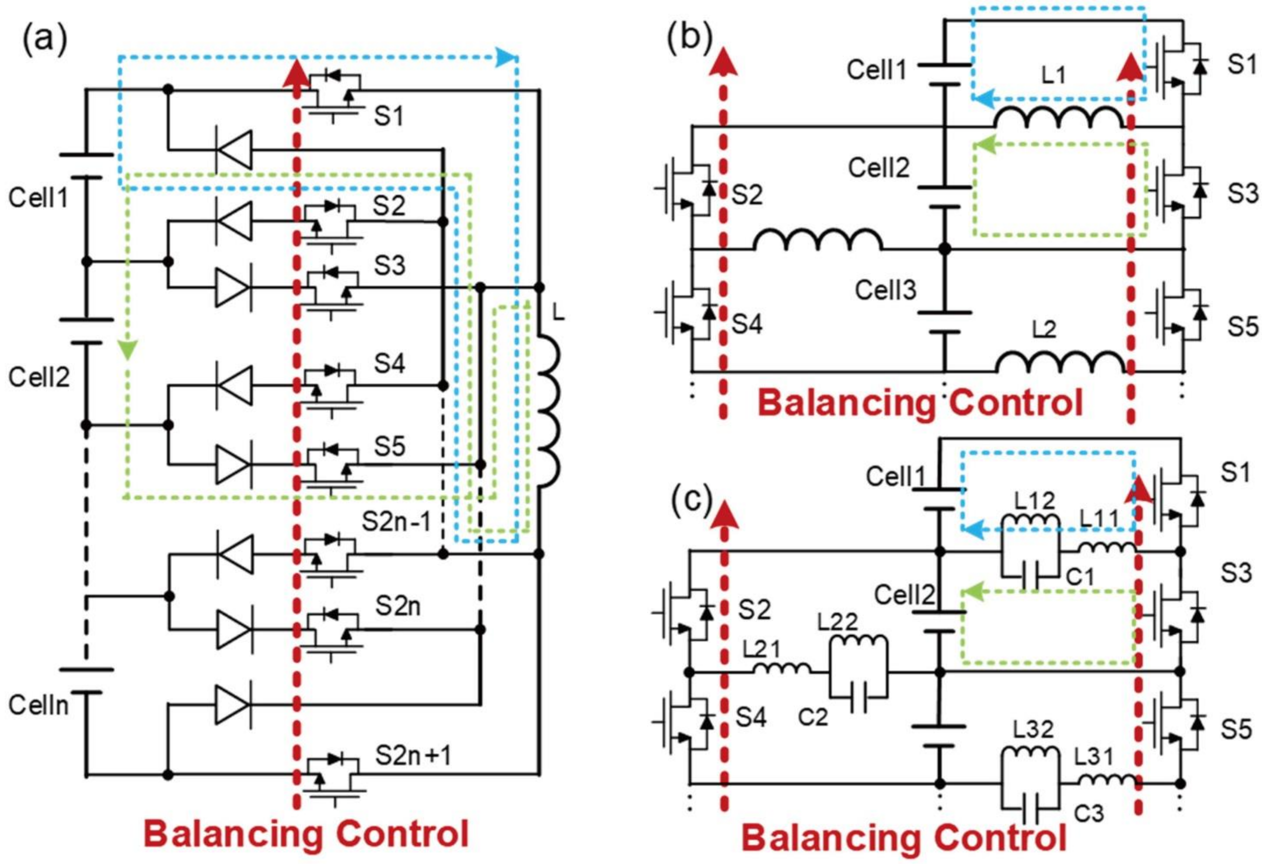

Fig. 7. Inductor based balancing topologies. (a) C2C single inductor topology. (b) C2C multiple inductors topology. (c) C2C resonant inductors topology.

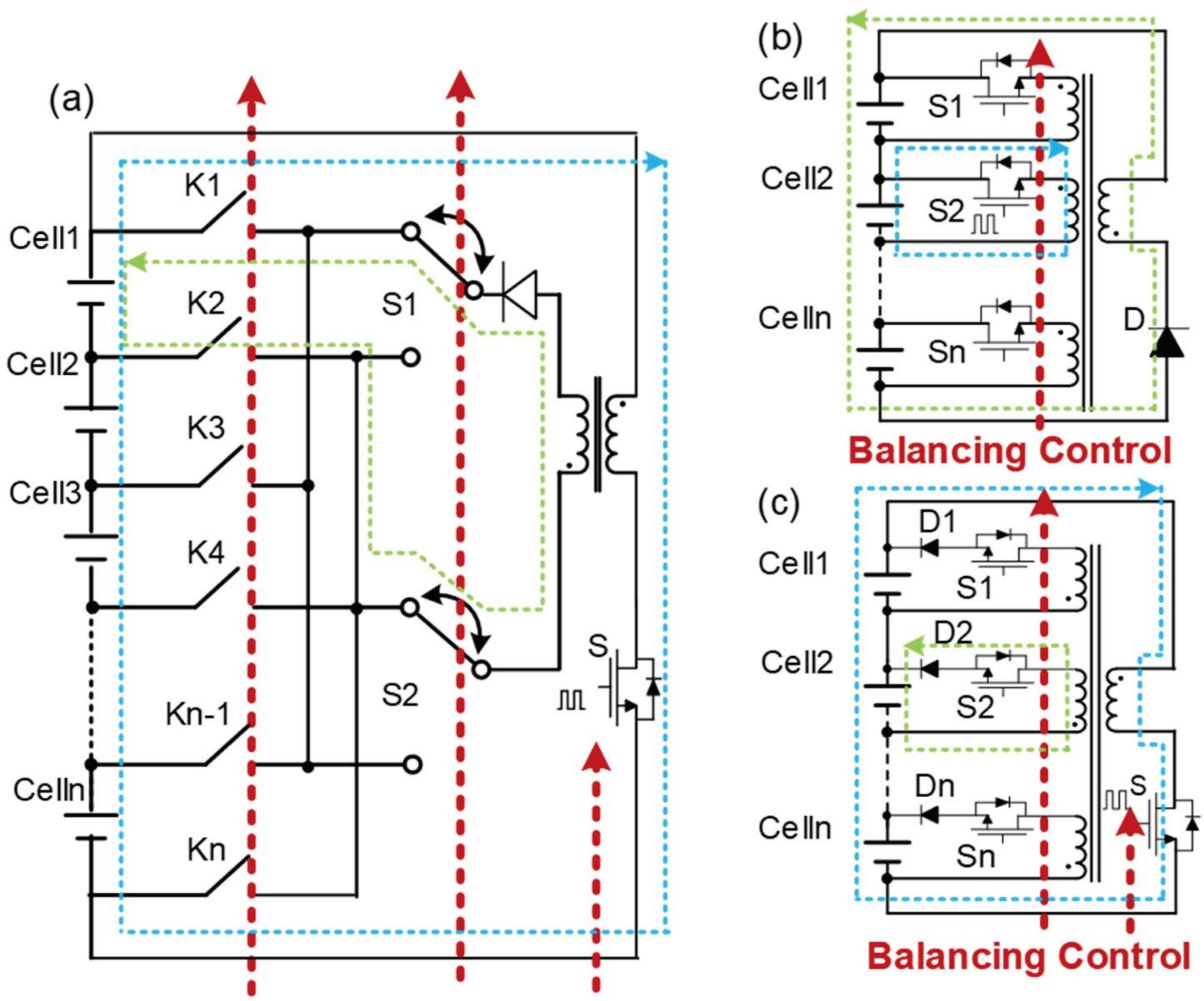

Fig. 8. Transformer based balancing topologies. (a) M2C single winding transformer topology. (b) C2M multiple windings transformer topology. (c) M2C multiple windings transformer topology.

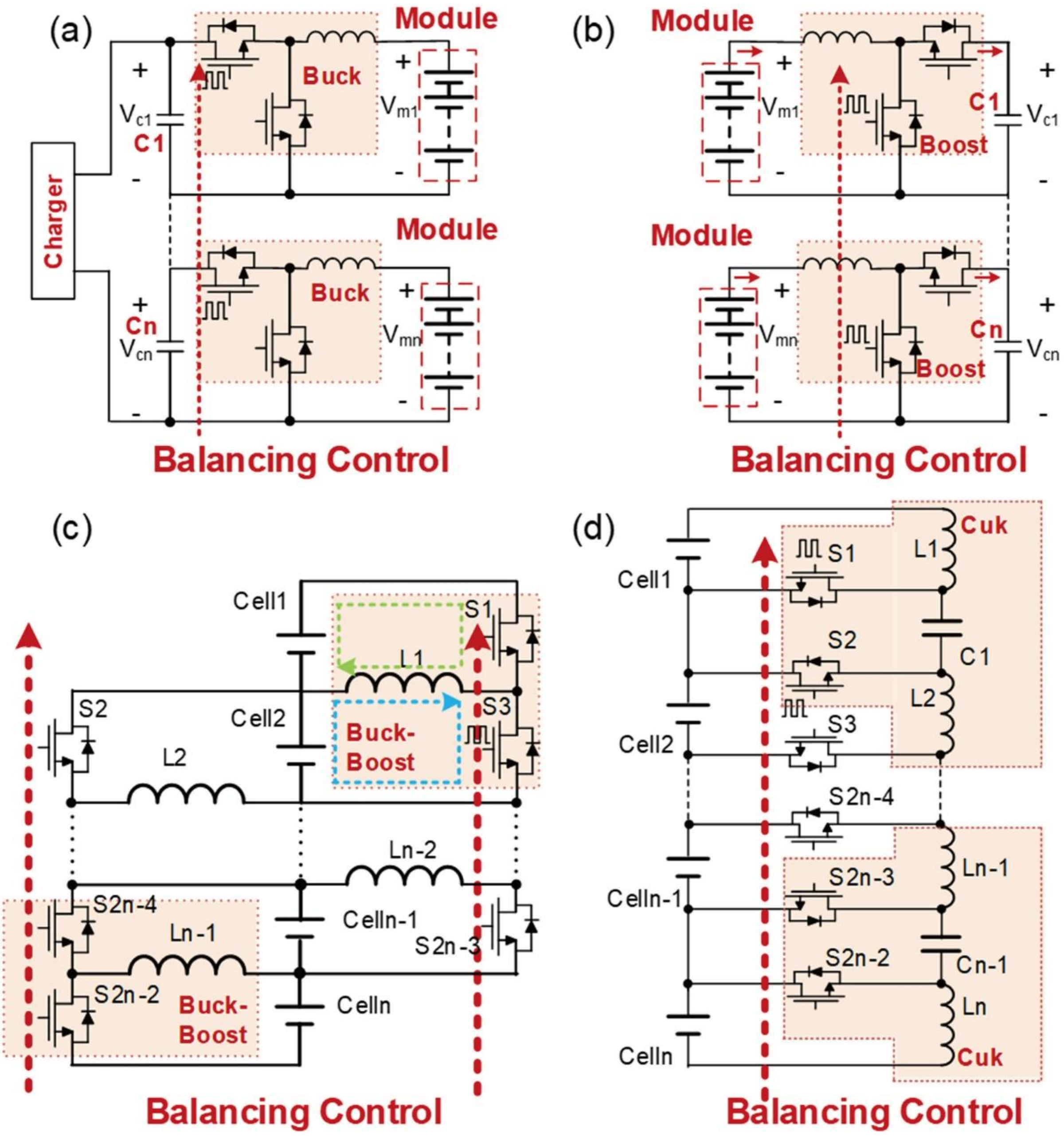

Fig. 9. DC/DC power converter based balancing topologies. (a) Charging Buck-based equalization topology. (b) Discharging Boost-based equalization topology. (c) C2C Buck-Boost topology. (d) C2C Cuk topology.

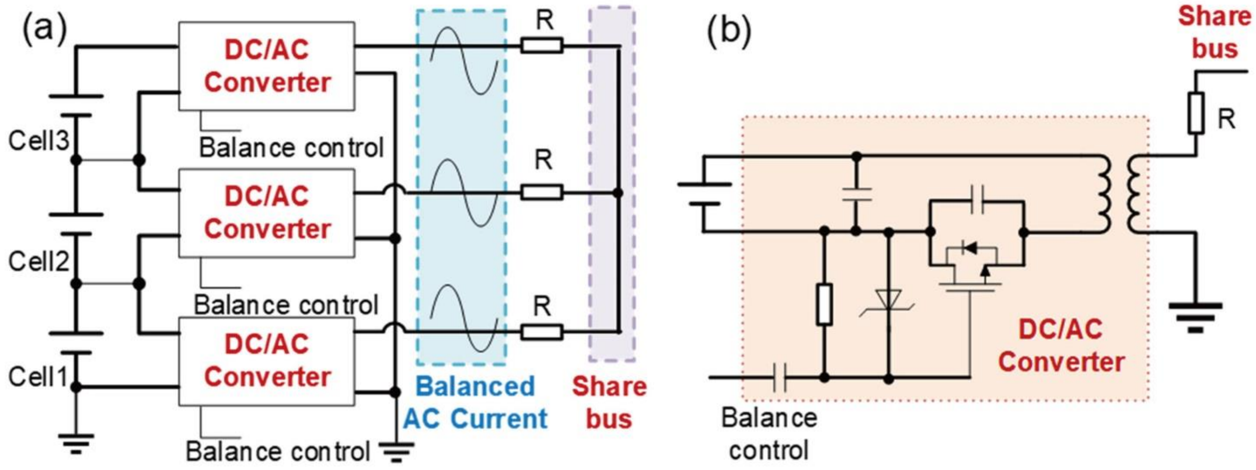

Fig. 10. Share bus based balancing topology. (a) Equalization topology. (b) DC/AC converter.

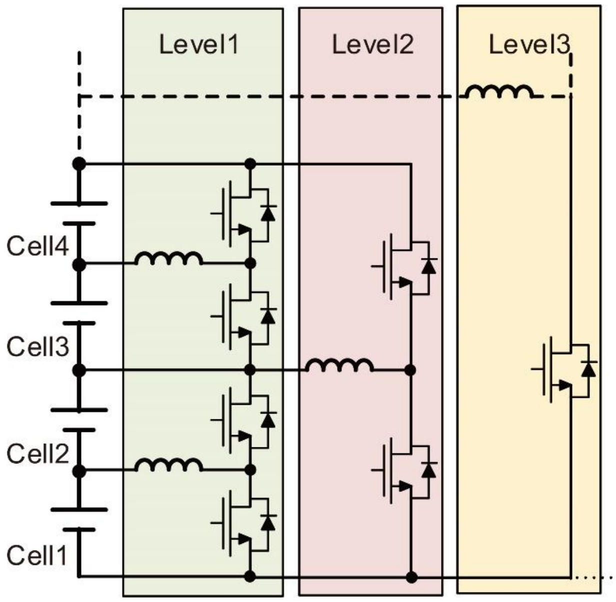

Fig. 11. Multi-levels equalization topology.

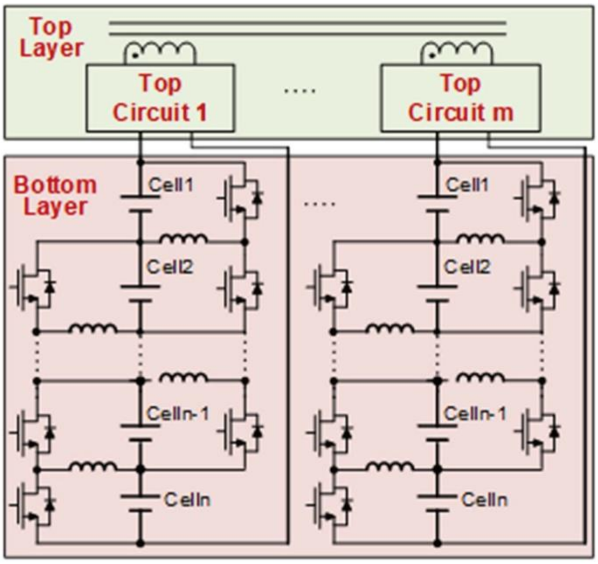

Fig. 12. Hierarchical balancing topology.

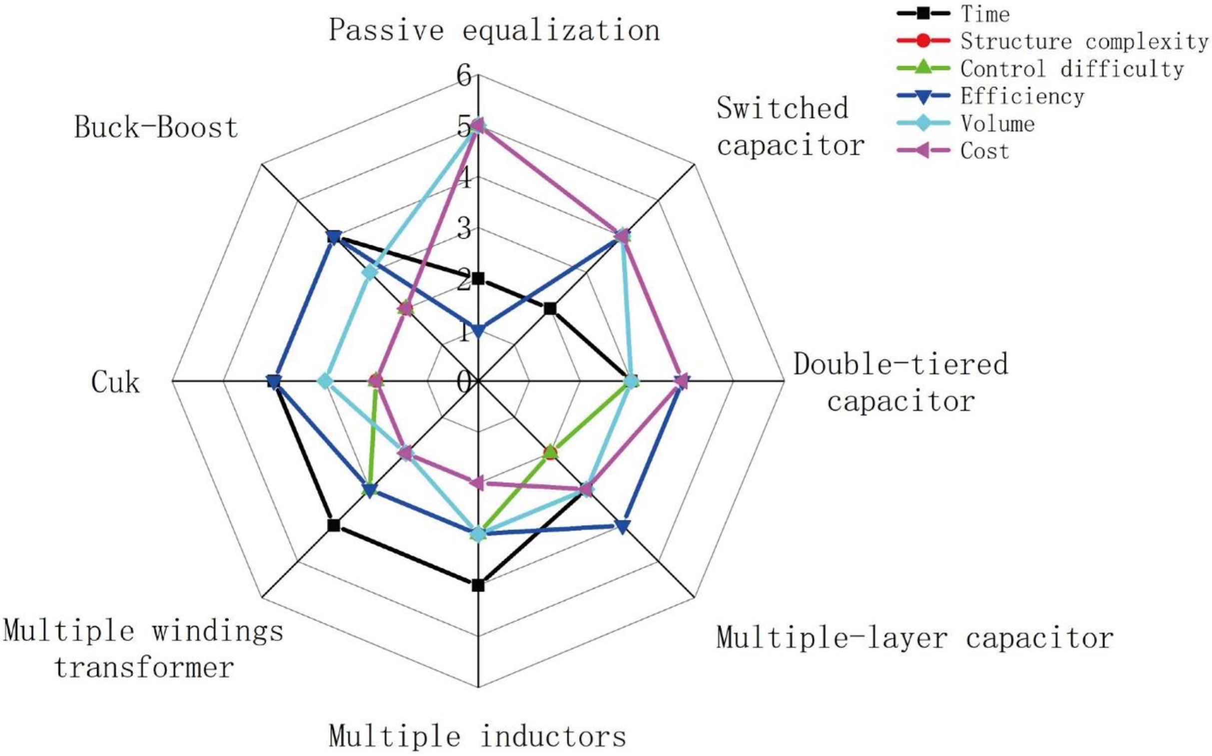

Fig. 13. Comprehensive comparison of different topologies.

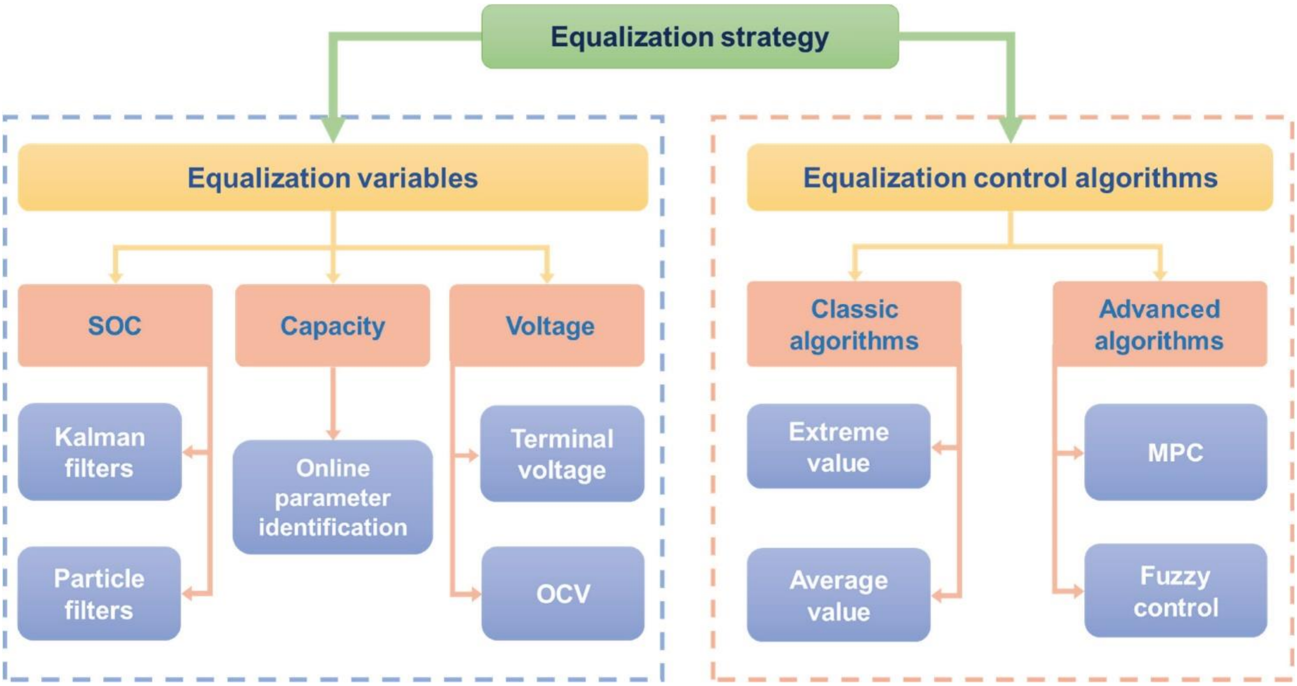

Fig. 14. The profile of equalization strategy and subsections.

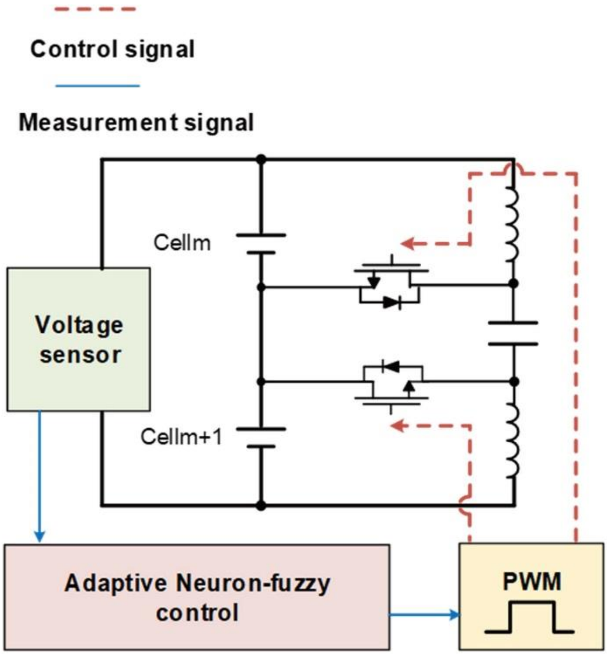

Fig. 15. The adaptive neural fuzzy network controller