

A Review of Supercapacitor Balancing Circuits

Yuhong FAN, Bowen PANG, Chao LIN, Minfan FU, and Hengzhao YANG

Abstract—The adoption of the supercapacitor technology in electrified transportation systems and renewable energy systems is accelerating. To enhance the safety and economy of supercapacitor energy storage systems, balancing circuits are typically required. This paper reviews the existing works on supercapacitor balancing. Basic balancing circuits based on resistors, capacitors, non-isolated and isolated converters, and resonant converters are covered. Advanced balancing circuits including modular circuits and reconfigurable circuits are also examined. As for the balancing circuit control strategy, distributed control, observer-based control, fuzzy control, and model predictive control are investigated. Furthermore, this paper proposes to conduct a holistic investigation of the existing and emerging topologies and control strategies of the balancing circuits to transform the empirical works on supercapacitor balancing to a general framework.

Index Terms—Balancing circuit, control strategy, supercapacitor, topology.

I. INTRODUCTION

SUPERCAPACITOR is an energy storage technology with a high power density and a long cycle life while its energy density is relatively low and its self-discharge rate is relatively high [1]–[3]. Energy storage systems based solely on supercapacitors or combining supercapacitors and other technologies such as batteries have been extensively investigated for transportation vehicles [4]–[13] and power systems [14]–[23]. For such high power applications, numerous supercapacitor cells are usually engineered in complex series and/or parallel configurations to build supercapacitor modules, packs, and systems. Given the variations of the physical parameters (e.g., capacitance and equivalent series resistance (ESR)) and the operating conditions (e.g., uneven temperature distribution in a module and differences in current/voltage stresses) of the supercapacitor cells, balancing circuits are typically required to ensure the proper operation and extend the lifetime of supercapacitor energy storage systems.

In fact, supercapacitor balancing has been briefly reviewed in the context of supercapacitor management [24]. Specifically,

the balancing circuits are roughly categorized as passive and active topologies. The passive category employs fixed and switched resistors while the active category utilizes capacitors, transformers, and DC-DC converters. Compared to supercapacitors, lithium-ion batteries show a much higher energy density and a much lower cost. Therefore, battery energy storage systems are more widely adopted in the industry.

Correspondingly, battery balancing has been extensively investigated [25]–[27]. While supercapacitors and batteries are two different energy storage technologies, their balancing issues are common in many aspects such as the goals (e.g., to balance the voltage, the state of charge (SOC), or the state of energy (SOE)) and the specific balancing circuit topologies (e.g., balancing circuits based on shunt resistors or Buck-Boost converters). Given these similarities, the balancing issues for batteries and supercapacitors have been reviewed together [28]. On the other hand, the characteristics of supercapacitors and batteries indeed differ. For instance, the operating voltage of a supercapacitor cell can be as low as zero, which is typically not the case with a battery cell. In the meantime, given the relatively low energy density and the relatively high power density of a supercapacitor cell, the balancing process can be much faster than that for a battery cell. While multiple extensive reviews for battery balancing [25]–[27] have been reported, this paper attempts to conduct a rather comprehensive review of the supercapacitor balancing issues although it also covers certain works on battery balancing.

The remainder of this paper is organized as follows. Section II examines the basic balancing circuits. Section III investigates the advanced balancing circuits. Section IV reviews the control strategies for balancing circuits. Section V concludes this paper and outlines the future work.

II. BASIC BALANCING CIRCUITS

A. Passive Balancing Circuits

1) Shunt resistor-based circuits: To balance supercapacitors [29] or batteries [30], shunt resistors can be utilized. As illustrated in Fig. 1, each supercapacitor cell is coupled with a shunt resistor of the same resistance. When the voltage of a particular cell is higher than the others, a larger discharging current flows through the shunt resistor to bring the cell voltage down. This balancing circuit is easy to implement. However, it always dissipates energy in the form of heat even when the supercapacitors are perfectly balanced, which introduces additional energy losses and may cause thermal management problems. Moreover, the resistance of the shunt resistor needs

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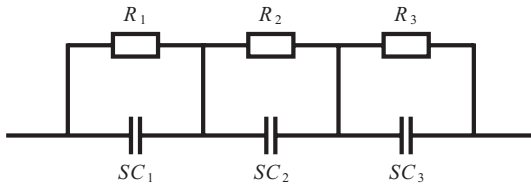


Fig. 1. Illustration of shunt resistor-based circuit.

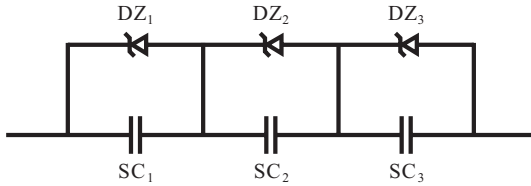


Fig. 2. Illustration of Zener diode-based circuit.

to be carefully determined to achieve a proper tradeoff between the balancing speed and the energy loss. If the resistance is too small, the discharging current may be too large and the corresponding energy loss is too much. On the other hand, if the resistance is too large, it may take too long to balance the supercapacitors because the discharging current is too small. To address these issues, balancing circuits based on Zener diodes and switched resistors have been proposed. Specifically, Zener diodes are mainly used to limit the excessively high cell voltages and they are typically in effect during the supercapacitor charging process. Switched resistors can be utilized to balance the cells during the supercapacitor charging and discharging processes.

2) Zener diode-based circuits: Zener diodes can be utilized for voltage balancing and overvoltage protection [31], [32], as illustrated in Fig. 2. The threshold of the Zener diode is set below the maximum operating voltage of the supercapacitor cell. When the cell voltage exceeds this threshold during the charging process, the Zener diode begins to conduct to limit the cell voltage from rising further. In the meantime, the other cells with lower voltages continue to charge until they reach the same voltage. Therefore, the voltages of all the cells are balanced and overvoltage protection is achieved. As another example, [33] proposes an Zener diode-based voltage regulating circuit to achieve dynamic balancing throughout the entire charging process while ensuring consistency between the supercapacitor cells. It should be noted that although Zener diode-based circuits can achieve voltage balancing to a certain extent and provide overvoltage protection for the cells exceeding the maximum operating voltage, they are still passive balancing circuits. Moreover, the threshold of the Zener diode is usually fixed, which limits the capability of the balancing circuit of adapting to different operating conditions. When the Zener diode is operating, energy is also dissipated as heat.

3) Switched resistor-based circuits: By introducing switched resistors, energy storage cells can also be balanced [34]–[37], as illustrated in Fig. 3. Specifically, a switch and a resistor are connected in parallel with each cell. When the voltage of a

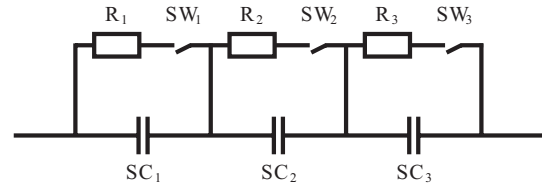


Fig. 3. Illustration of switched resistor-based circuit.

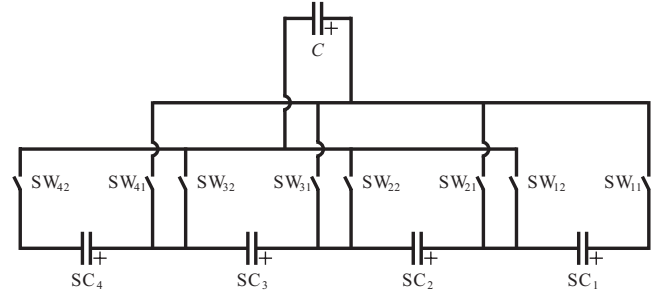


Fig. 4. Illustration of single capacitor-based circuit.

cell exceeds a predefined threshold, the corresponding switch is closed and a current flows through the resistor to discharge this particular cell. This method can also provide overvoltage protection. When the switches are controlled independently, the cells can be discharged selectively, which means that active control is feasible in these circuits. Consequently, various control strategies [38] have been proposed, which include recursive least square (RLS) methods [39], PI controllers [40], [41], model predictive control (MPC) schemes [42], generalized extended state observers (GESOs) [43], and pinning control schemes [44]. Although switched resistor-based balancing circuits are also dissipative circuits, compared to shunt resistor-based and Zener diode-based balancing circuits, they provide a more flexible control of the discharging process through the switched resistors to reduce the energy loss.

B. Switched Capacitor-Based Balancing Circuits

Switched capacitor-based balancing circuits use one or multiple capacitors as the buffer to transfer energy from high-voltage cells to low-voltage cells. Such circuits can be further divided into four categories based on the specific implementation of the energy buffer: single capacitor-based circuits, multiple capacitor-based circuits, switched LC-based circuits, and Cockcroft-Walton (CW) circuits.

1) Single capacitor-based circuits: A single capacitor-based balancing circuit [45], [46] is illustrated in Fig. 4. To balance two cells with different voltages, the capacitor is first connected to the high-voltage cell to absorb energy by properly configuring the switches. Then, the capacitor is connected to the low-voltage cell to release energy. Since only a single capacitor is involved, this circuit is cost effective. Moreover, this circuit is flexible in that it can select the specific cells to be balanced. However, the balancing speed of this circuit depends on the voltage difference between the cells, which means that

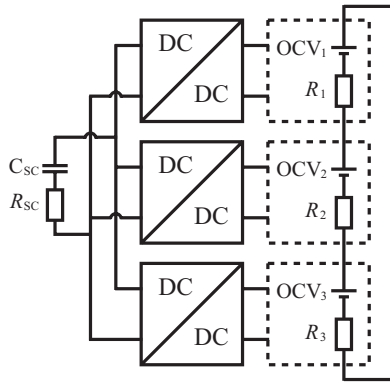


Fig. 5. Single capacitor-based circuit proposed in [49].

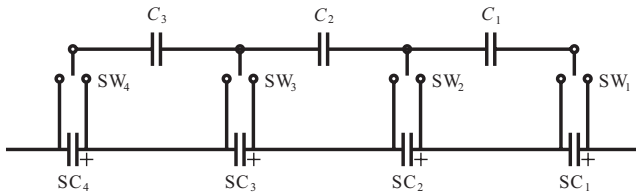


Fig. 6. Illustration of multiple capacitor-based circuit.

it may take a long time to balance the cells when the voltage difference is relatively small.

Other than using a single capacitor, more complex implementations of the energy buffer have been proposed. For instance, a device made of capacitors and switches serves as the energy buffer to achieve faster balancing [47]. Moreover, on top of a single capacitor, power converters can be added to accelerate the balancing process when the voltage difference is relatively small [48]–[54], as illustrated in Fig. 5.

2) Multiple capacitor-based circuits: A balancing circuit employing multiple capacitors is illustrated in Fig. 6. Keeping the single-pole double-throw switches toggling can balance the two adjacent cells connected by a capacitor. In particular, for hybrid energy storage systems composed of batteries and supercapacitors, it is beneficial to reuse the supercapacitors as the energy buffer to balance the systems [55]–[59]. Although this method cannot select specific cells for balancing, it can balance all the cells over the time. Similar to the single capacitor-based circuit, the balancing speed of the multiple capacitor-based circuit is also affected by the voltage difference between the cells. For the balancing circuits based on one or multiple capacitors, the switches are hard switched. Therefore, a large transient current may occur during the switching process, which may affect the reliability of the switches and the energy storage cells.

3) Switched LC-based circuits: To address the issues with switched capacitor-based circuits, switched LC-based circuits are proposed, which replace the capacitors using LC units composed of an inductor and a capacitor connected in series. By setting the switching frequency close to the resonant frequency, the LC unit can achieve resonance, thus enabling efficient energy transfer and soft switching. Still, the energy

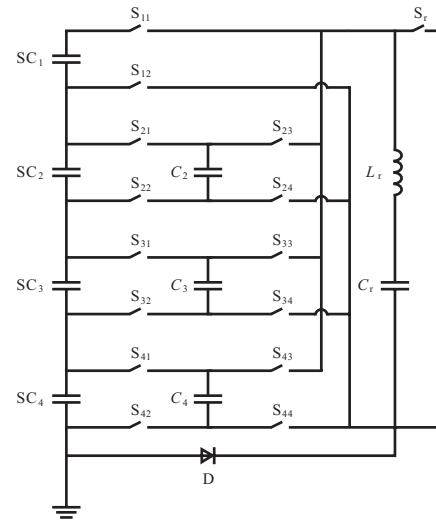


Fig. 7. Switched LC-based circuit proposed in [62].

transfer efficiency of a switched LC-based circuit is affected by the voltage difference between the energy storage cells.

As illustrated in Fig. 7, a single LC unit is combined with a switch network to transfer energy between the energy storage cells [60]–[62]. Multiple LC units can be adopted to accelerate the energy transfer process [63]. Moreover, multiple LC units can be combined with CW circuits to optimize the control strategies [64]–[66]. A multi-layer switched LC-based circuit with soft switching is proposed in [67].

4) CW circuits: Instead of using switches, an AC source and multiple diodes can be used in a CW circuit to balance the energy storage cells, as illustrated in Fig. 8(a). The CW circuit is also known as the multiplier circuit or the voltage doubler circuit. When the AC source polarity is positive, certain diodes conduct and the capacitors are charged, as illustrated in Fig. 8(b). When the AC source polarity is negative, the remaining diodes conduct and the stored charge is redistributed to the other capacitors or the energy storage cells, as illustrated in Fig. 8(c). Through this alternating charging and discharging process, the voltage difference between adjacent cells can be gradually reduced and balancing can be achieved.

Compared to switched capacitor-based circuits that rely on actively controlled switches, the CW circuit implements part of the switching operation using diode rectification and reduces the number of switches. Consequently, the CW circuit structure is relatively simple. Moreover, the CW circuit can provide continuous balancing under repetitive AC excitations. However, the CW circuit operates in a relatively fixed pattern and its balancing performance is dependent on the frequency and amplitude of the AC source. Moreover, the reduction in the switch count of the CW stage does not necessarily imply a lower complexity at the system level because an additional AC excitation stage is often required in practice. Therefore, the advantages of the CW circuit in terms of hardware simplicity should be evaluated together with the cost, controllability, and implementation difficulty of the external AC source.

Reference [68] provides a detailed analysis of the CW circuit

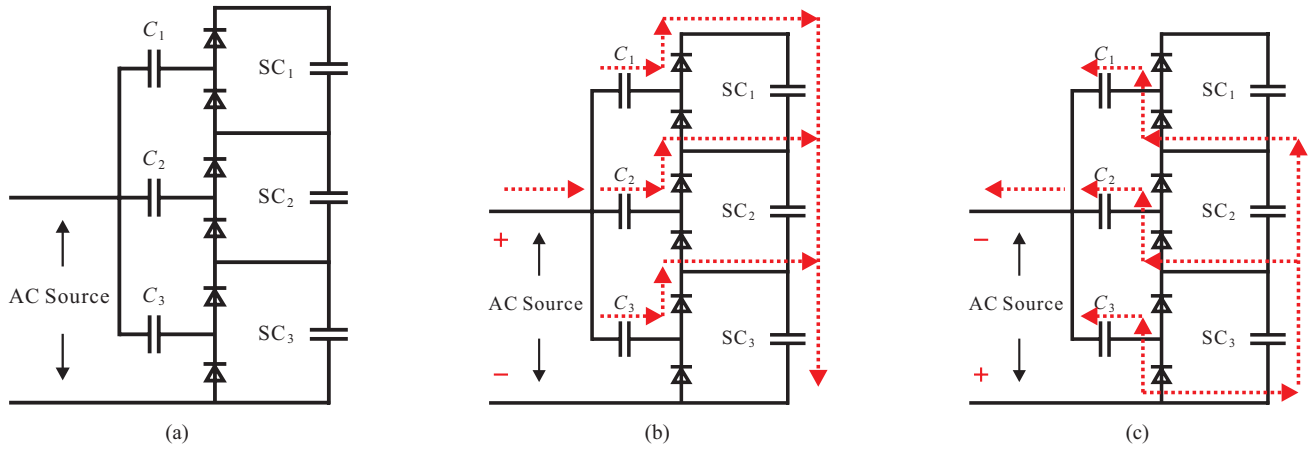


Fig. 8. CW circuit. (a) Schematic. (b) Operation mode when AC source polarity is positive. (c) Operation mode when AC source polarity is negative.

operation and introduces several balancing solutions based on the CW circuit. It has been demonstrated that the CW circuit is often used as part of a larger balancing circuit [69]–[71]. In fact, the CW circuit has been combined with the series resonant circuit [72], the full-bridge circuit [73], the switched LC circuit [65], [66], and the SEPIC circuit [74], [75] to generate the required AC excitation or to balance the energy storage cells. These examples show that the CW circuit is more suitable for applications requiring a reduced switch count and continuous balancing while its main bottlenecks lie in the limited control flexibility and the need for the external AC excitation.

C. Non-Isolated PWM Converter-Based Balancing Circuits

To achieve better balancing performance, numerous types of power converters have been explored. In general, power converters can be divided into pulse width modulation (PWM) converters and resonant converters. PWM converters can be further categorized as non-isolated converters without transformers and isolated converters with transformers. Therefore, this section focuses on the balancing circuits based on non-isolated PWM converters while Sections II-D and II-E examine the balancing circuits based on isolated PWM converters and resonant converters, respectively. When non-isolated PWM converters are used for balancing, they must be bidirectional to ensure that balancing can be carried out normally. Therefore, this section reviews the Buck-Boost, Cuk, SEPIC, and Zeta converters for balancing applications.

1) Circuits based on Buck-Boost converters: As illustrated in Fig. 9, a bidirectional Buck-Boost converter can be used to balance two energy storage cells. Specifically, the two cells are connected in series, the inductor is connected to the midpoint of the two cells, and the two switches alternately connect the circuit to the upper and lower sides. Consequently, energy can be transferred from the cell with a higher voltage to the cell with a lower voltage. The bidirectional characteristic is critical because it allows both step-up and step-down operations in the same topology, which makes the energy transfer more flexible according to the voltage distribution of the cells. Moreover, the Buck-Boost converter has continuous input and output

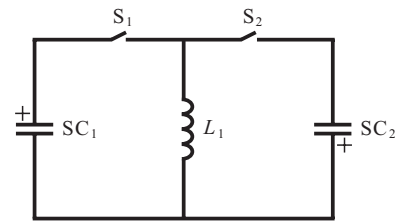


Fig. 9. Illustration of Buck-Boost converter-based circuit.

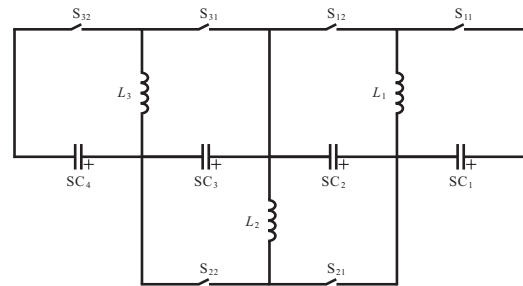


Fig. 10. Buck-Boost converter-based circuit proposed in [79].

currents, a relatively simple topology, and a convenient control over the current. These characteristics help reduce the current stress on the energy storage cells. Therefore, the Buck-Boost converter can be used to balance both supercapacitors and batteries. However, in its basic form, the Buck-Boost converter can only balance adjacent cells, which means that its scalability is limited. To balance more cells, additional switch networks, hierarchical structures, or modular extensions are often required. Therefore, the Buck-Boost converter can provide a good balance among the balancing speed, control flexibility, and circuit complexity.

A common configuration of the Buck-Boost converter-based balancing circuit [76]–[79] is shown in Fig. 10. Inserting a Buck-Boost converter between any two neighboring energy storage cells enables the balancing of these two cells, which in turn facilitates the balancing of all the cells.

This common configuration is improved by introducing capacitors [80], [81], as shown in Fig. 11. With these capacitors,

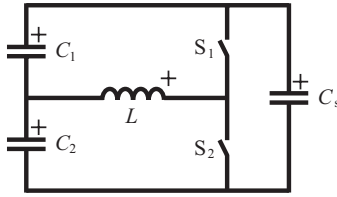


Fig. 11. Buck-Boost converter-based circuit proposed in [81].

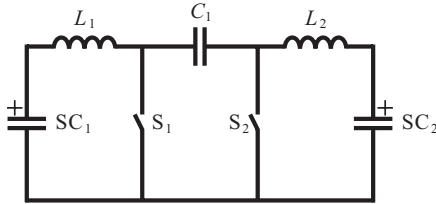


Fig. 12. Illustration of Cuk converter-based circuit.

it is possible to eliminate the voltage spikes and provide soft switching characteristics to enhance the performance of the Buck-Boost converter. As another enhancement, autonomous balancing is achieved using a fixed duty cycle switch control method, which means that regardless of the voltage distribution among the cells, the circuit can achieve balancing through a fixed operating mode with a 50% complementary duty cycle [82], [83].

To provide a more flexible balancing path than the common configuration, a hierarchical structure is introduced [84], [85]. To implement energy transfer between any two cells, a switch network is combined with the Buck-Boost converter [86]. This circuit reduces the number of Buck-Boost converters and enhances the selectivity of the balancing circuit. However, the downside is that this circuit can only transfer energy between two specific cells at a time and cannot achieve simultaneous balancing among more cells.

2) Circuits based on other non-isolated converters: Apart from the Buck-Boost converter, other non-isolated power converters used for balancing include the Cuk, SEPIC, and SEPIC-Zeta topologies.

A Cuk converter can drain energy from the energy storage cells, as illustrated in Fig. 12. This converter is particularly useful for applications in which the input and output voltages are of different polarities. By introducing inductors for both the input and the output, this circuit generates a favorable output current waveform. The Cuk converter has been employed in various balancing circuits. For instance, Fig. 13 shows that the Cuk converter is employed to connect adjacent cells to achieve balancing [87]. By introducing a bus topology, any two Cuk converters can be connected [88], [89]. A capacitor-isolated Cuk converter-based balancing circuit is proposed in [88]. Similarly, a transformer-isolated Cuk converter-based balancing circuit is proposed in [90]. A switch network [90], [91] and an integrated configuration [92] are employed to minimize the component count and improve the selectivity of Cuk converter-based balancing circuits, respectively.

As illustrated in Fig. 14, the SEPIC converter can generate an output voltage that can be higher than, lower than, or equal

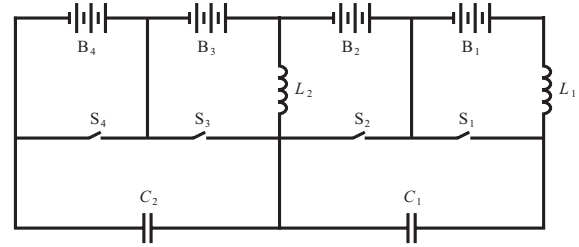


Fig. 13. Cuk converter-based circuit proposed in [87].

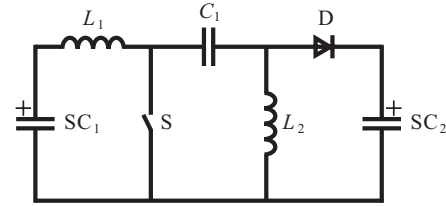


Fig. 14. Illustration of SEPIC converter-based circuit.

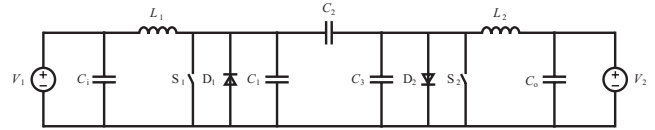


Fig. 15. SEPIC converter-based circuit proposed in [94].

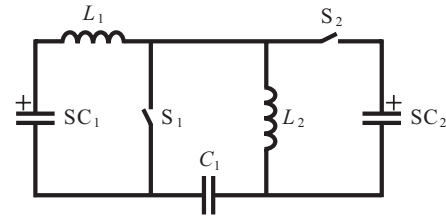


Fig. 16. Illustration of SEPIC-Zeta converter-based circuit.

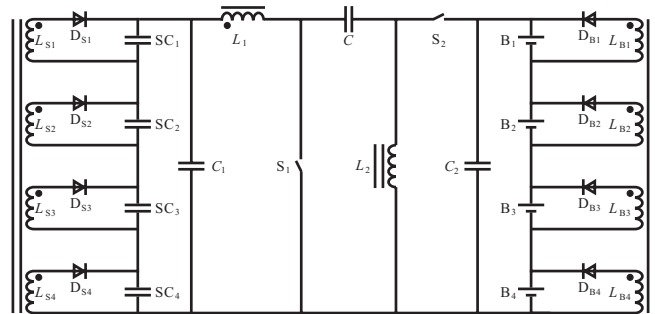


Fig. 17. SEPIC-Zeta converter-based circuit proposed in [96].

to the input voltage [93]. For instance, Fig. 15 shows a high-frequency bidirectional SEPIC converter with small magnetic components for balancing applications [94].

The SEPIC-Zeta converter integrates the features of the SEPIC and Zeta converters, as illustrated in Fig. 16. For instance, efficient bidirectional energy transfer can be implemented using the SEPIC-Zeta converter [95], [96], as shown in Fig. 17.

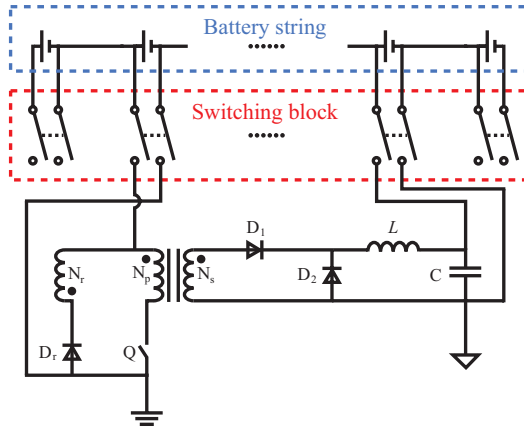


Fig. 18. Forward converter-based circuit proposed in [97].

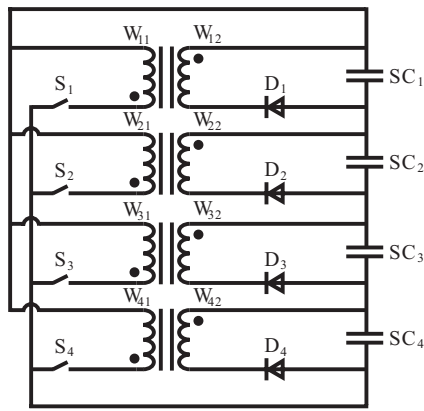


Fig. 19. Flyback converter-based circuit proposed in [98].

D. Isolated PWM Converter-Based Balancing Circuits

1) Circuits based on forward and flyback converters: This section reviews the isolated PWM converters used for balancing energy storage cells. In general, forward converters have higher efficiencies and lower switching losses while flyback converters feature simpler configurations and lower costs. For balancing applications, forward converters are not commonly adopted because they are not suitable for multiple outputs. For instance, a forward converter is combined with a switch network to achieve selective balancing [97], as illustrated in Fig. 18.

Compared to forward converters, flyback converters are more suitable for balancing applications. For example, multiple flyback converters are employed in a balancing circuit [98], as shown in Fig. 19. In particular, by connecting all the primary sides of the flyback converters to the entire energy storage string and the secondary sides to the individual cells, it is possible to transfer energy to any cell and balance all the cells simultaneously. Similarly, an input-series-output-series (ISOS) flyback converter is employed [99]. Moreover, a switch network is combined with a flyback converter to reduce the number of components [100].

Forward and flyback converters can be combined to improve the balancing speed and reduce the driving cost [101]–[103], as

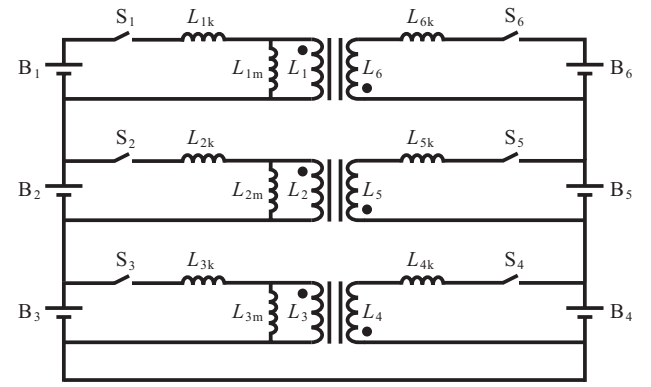


Fig. 20. Balancing circuit combining forward and flyback converters [101].

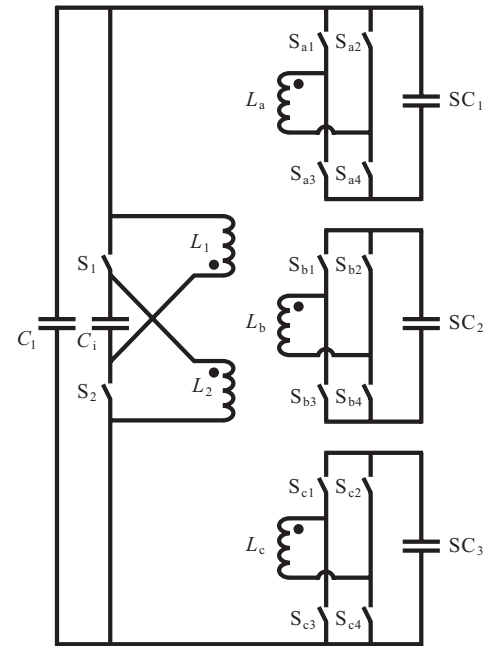


Fig. 21. Push-pull converter-based circuit proposed in [104].

illustrated in Fig. 20.

2) Circuits based on push-pull converters: Compared to forward and flyback converters, push-pull converters can generate larger balancing currents. Moreover, push-pull converters can implement synchronous rectification to reduce the power loss and improve the balancing efficiency. For instance, a push-pull converter-based balancing circuit with a multi-winding transformer is proposed for supercapacitor energy storage systems [104], as shown in Fig. 21. This circuit uses controllable power MOSFETs instead of power diodes for full-bridge rectification to increase the balancing speed and reduce the power loss. Also based on a multi-winding transformer, an improved voltage balancing strategy is proposed and the transient performance is improved by inserting a clamping capacitor on the primary side of the transformer [105]. For a supercapacitor energy storage system, a push-pull converter is utilized to transfer energy between the supercapacitor modules at low operating voltages to achieve balancing [106].

3) Circuits based on half-bridge and full-bridge converters:

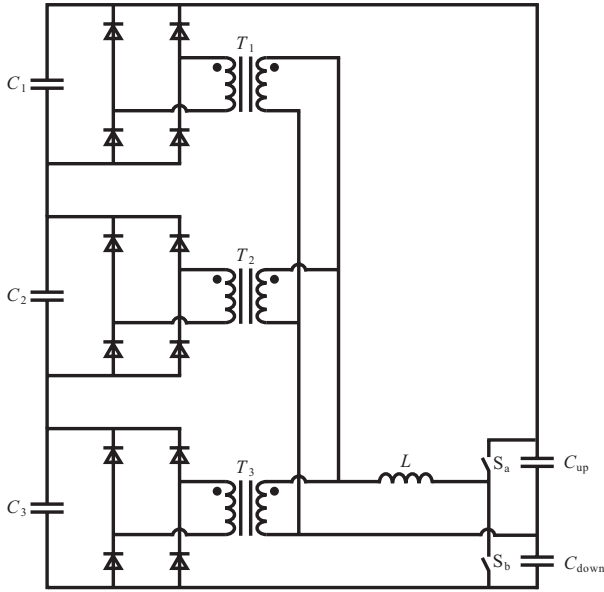


Fig. 22. Half-bridge converter-based circuit proposed in [109].

Half-bridge and full-bridge converters are also used in balancing circuits. Compared to push-pull converters, half-bridge and full-bridge converters can withstand higher input voltages. Therefore, they are more suitable for balancing large energy storage systems. Half-bridge converters typically include two switches and two capacitors [107], [108]. When neither switch is turned on, the capacitors split the input voltage in half. When one switch is turned on, the load is connected to the input voltage. When the other switch is turned on, the load is connected to the ground. For instance, two energy storage cells are integrated in a half-bridge structure to reduce the number of components [109], as shown in Fig. 22. Moreover, the half-bridge converter can be combined with a CW circuit to reduce the number of switches and magnetic components [110], [111]. As another example, the half-bridge converter is combined with a multi-winding transformer to achieve balancing [112].

On the other hand, full-bridge converters include four switches and they can provide a better power conversion capability than half-bridge converters. Full-bridge converters can more flexibly control the output voltage and the output current, which is particularly useful for applications that require large balancing currents [113], [114]. For example, a full-bridge converter is combined with a switch network to achieve balancing [115], as shown in Fig. 23. This solution uses fewer components compared to multi-winding transformers and multiple converters. The full-bridge converter can also be combined with a CW circuit to achieve balancing [73]. As another example, the full-bridge converter is combined with a multi-winding transformer to balance multiple energy storage modules [116].

E. Resonant Converter-Based Balancing Circuits

1) Circuits based on series resonant converters: As illustrated in Fig. 24, series resonant converters can be used for voltage balancing [117]. The series resonant converter consists of an

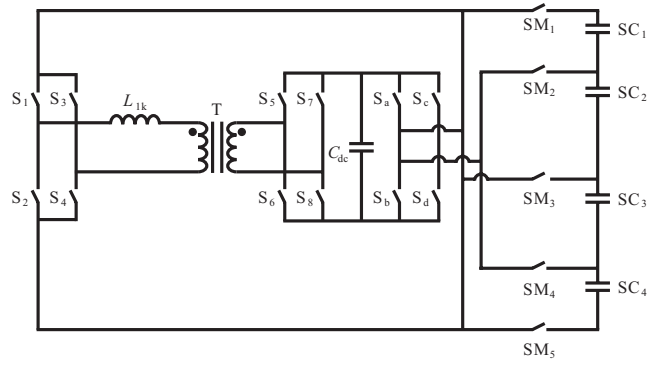


Fig. 23. Full-bridge converter-based circuit proposed in [115].

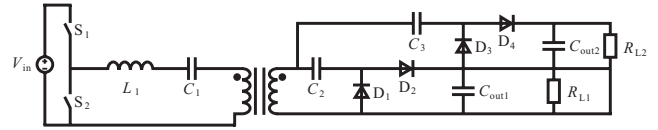


Fig. 24. Series resonant converter-based circuit proposed in [117].

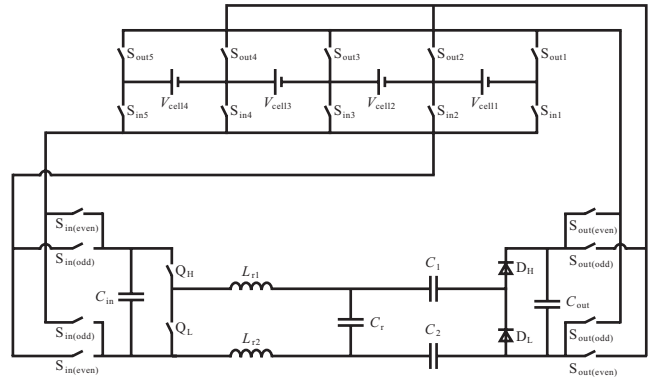


Fig. 25. Parallel resonant converter-based circuit proposed in [118].

inductor and a capacitor in series with the load. Since they can generate constant currents, series resonant converters can be used for voltage balancing to avoid arcing on the energy storage cells that could damage the cells.

2) Circuits based on parallel resonant converters: Parallel resonant converters can also be used for voltage balancing [118], as illustrated in Fig. 25. This circuit uses capacitors instead of transformers for isolation to reduce the circuit size. In this circuit, the inductor and the capacitor are connected in parallel with the load. Parallel resonant converters can also generate constant currents, particularly at a fixed switching frequency, which ensures that the balancing circuit can operate safely without feedback control even when the voltage of a particular energy storage cell drops to zero.

3) Circuits based on LLC resonant converters: An LLC resonant converter-based balancing circuit [119] is illustrated in Fig. 26. This circuit incorporates the features of series and parallel resonant circuits into an LLC resonant tank. Since this topology can limit the current, it ensures a safe operation during the voltage balancing process. Moreover, LLC resonant converters can realize a relatively high power conversion efficiency with soft switching, which reduces the switching loss

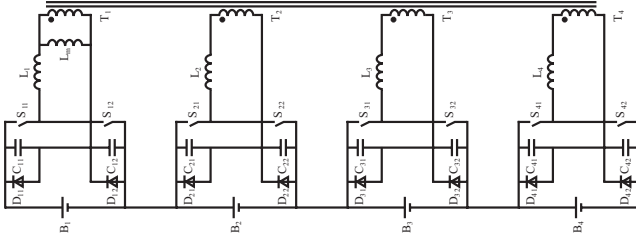


Fig. 26. LLC resonant converter-based circuit proposed in [119].

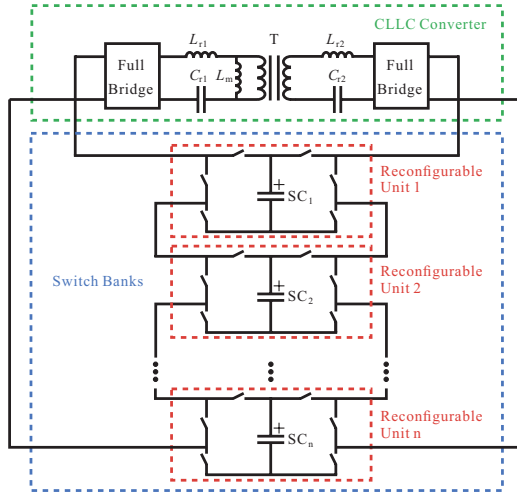


Fig. 27. CLLC resonant converter-based circuit proposed in [127].

and the thermal stress. The LLC resonant converters are further optimized to improve the balancing speed and efficiency [120], [121].

4) Circuits based on CLLC resonant converters: Compared to LLC resonant converters, CLLC topologies can implement bidirectional energy transfer, which means that a variety of energy flow paths can be established to enhance the flexibility of the balancing circuit [122], [123]. For instance, AC-to-AC balancing is implemented using a CLLC converter [124]. To reduce the stresses on the switching devices, an ISOS CLLC topology is proposed [125]. Moreover, a CLLC converter is utilized to develop a reconfigurable balancing circuit for supercapacitors [126], [127], as illustrated in Fig. 27. Each supercapacitor is coupled with a bank of six switches. By properly configuring the switches, the supercapacitors can be grouped and connected to the CLLC ports. The CLLC converter can be utilized to implement bidirectional energy flows between two groups of supercapacitors to achieve balancing.

III. ADVANCED BALANCING CIRCUITS

A. Modular Circuits

To balance large energy storage systems, modular design is an effective approach since each module of the circuit can work independently to enhance the system reliability or jointly to improve the system scalability. For example, a modular balancing circuit based on a multi-winding transformer is

proposed for a battery energy storage system, which employs both the forward converter and the flyback converter [128]. Specifically, the forward converter is used to balance the cells within the same module while the flyback converter is used to balance different modules. As another example, a modular design with a multi-winding transformer is proposed for a supercapacitor energy storage system [129]. Within the modules, flyback converters are employed to balance the supercapacitor cells. Between the modules, Boost converters are adopted to achieve balancing. Moreover, a modular design based on bidirectional Buck-Boost converters is proposed, which implements inter-module balancing using these Buck-Boost converters [130]. For intra-module balancing, a half-bridge converter and a CW circuit are utilized. In [131], a modular design is proposed for a supercapacitor energy storage system, which employs Buck-Boost converters for intra-module balancing and LC resonant converters for inter-module balancing, respectively.

For modular circuits, modular multilevel converters (MMCs) are widely adopted, which usually convert DC power to AC power through multiple interconnected modules, enabling high-precision voltage control [132]. An MMC is composed of multiple modules and each module typically includes an H-bridge with four switching devices and one or more capacitors. By independently adjusting the switching states of these devices, each module can produce several different voltage levels (typically three: positive voltage, zero voltage, and negative voltage). When many of such modules are connected in series, they can synthesize smooth voltage waveforms that are close to ideal sine waves. Since an MMC can directly control the inclusion or exclusion of individual energy storage cells in the circuit, an MMC can be used for balancing. For instance, an MMC is utilized to balance the supercapacitor SOC for applications in microgrids [133] and high-speed traction drives [134], respectively.

The MMC structure illustrated in Fig. 28 is employed to balance the SOC and voltages of the supercapacitors and batteries in a hybrid energy storage system [135], [136]. Specifically, the module SOC is arranged in the descending order and the carrier waves are cascaded. The PWM signal for each module is generated by comparing the reference voltage with the cascaded carrier waves. In this way, the cells with lower SOC are connected to the circuit for less time and their SOC decreases less, which helps reduce the differences between the SOC to achieve balancing.

Reference [137] proposes an SOC balancing control strategy for an MMC-based supercapacitor energy storage system. This strategy applies SOC-based deceleration control to achieve SOC balancing during charging and discharging processes. Independent voltage and current loops are constructed for each module. To balance the SOC, the SOC of each module is introduced to the current loop, allowing each module to adjust its average operating current based on its own SOC. The proposed strategy also provides a satisfactory DC bus voltage regulation capability and eliminates the communication lines, making the modules independent of each other. Similarly, to

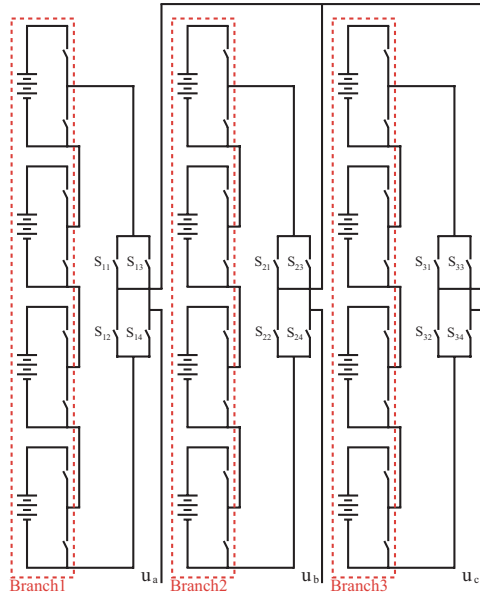


Fig. 28. Illustration of MMC [136].

minimize the system current deviations caused by the balancing algorithm, a concise unidirectional current compensation method is proposed [138].

Reference [139] proposes a power sharing strategy to balance the supercapacitors. Specifically, it considers a modular architecture by equipping each supercapacitor with a power converter and interconnecting all the supercapacitors through the converters for rapid charging and balancing. In particular, it proposes a control saturation-adaptive voltage balancing strategy. The strategy predicts and identifies which converters would saturate before control saturation occurs by setting thresholds and conducting checks. Consequently, the converters predicted to saturate are intentionally allowed to do so at the beginning to reduce their energy shares, which ultimately leads to voltage balancing.

B. Reconfigurable Circuits

A reconfigurable circuit in the context of energy storage systems usually refers to a circuit that can change the connection modes of the cells as needed. For example, when a higher output current or voltage is needed, the cells can be configured in parallel or series, respectively. Consequently, in a reconfigurable circuit, the current passing through each cell during the charging and discharging processes can be tuned to balance the system. In fact, various reconfigurable circuit topologies and control strategies have been proposed [140]–[142].

Reference [143] analyzes the design of a reconfigurable circuit for a battery module that consists of a string of battery cells. It proposes a modular reconfigurable battery pack (MRBP), which is composed of reconfigurable battery modules (RBMs) and H-bridge converters. All the RBMs in the MRBP are cascaded to produce a stepped positive voltage waveform. The H-bridge converter is utilized to reverse the polarity of the stepped voltage to form a multilevel AC voltage. Therefore,

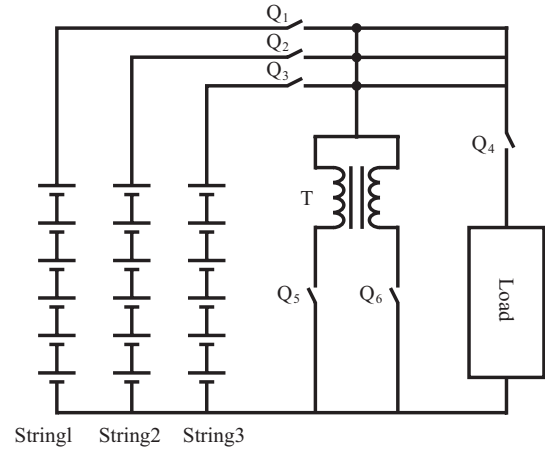


Fig. 29. Reconfigurable circuit proposed in [146].

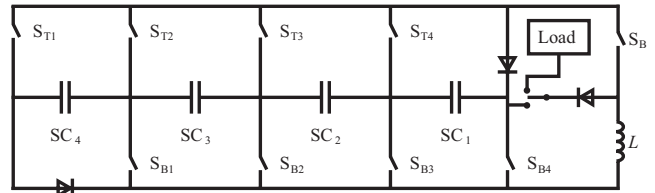


Fig. 30. Reconfigurable circuit proposed in [147].

the RBM output characteristics can be reconfigured. The modularity and reconfigurability of this circuit contribute to the high reliability and fault tolerance of the system.

Beyond altering the output characteristics of energy storage systems, reconfigurable circuits can also be used to balance energy storage systems. For example, [144] demonstrates the impact of reconfigurable circuits on energy storage system balancing through theoretical analyses and empirical validations. Specifically, three levels of reconfigurable models are proposed and analyzed. It is concluded that the higher the reconfigurability of the energy storage module, the better the balancing performance.

When reconfigurable circuits are used for balancing energy storage systems, different numbers of switching devices can be incorporated to achieve different degrees of reconfigurability [145]. For instance, Fig. 29 shows an energy storage module with multiple parallel strings [146]. Each string is connected to the transformer through a switch. By properly controlling the switches, energy can be transferred between different strings. Since the circuit reconfigurability is relatively low, while the strings as a whole can be balanced, a specific cell cannot be balanced. References [147] and [148] equip each energy storage cell with two switches, as shown in Fig. 30. By properly toggling the switches, it is possible to isolate a specific part of the entire battery string and connect it to the circuit while leaving the rest disconnected. Therefore, certain cells can be manipulated and the circuit reconfigurability is improved.

References [149] and [150] couple each battery cell with three switches and allow the cell to perform series, parallel, and bypass operations with the adjacent cells or the bus, enhancing

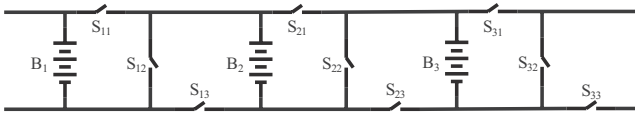


Fig. 31. Reconfigurable circuit proposed in [149].

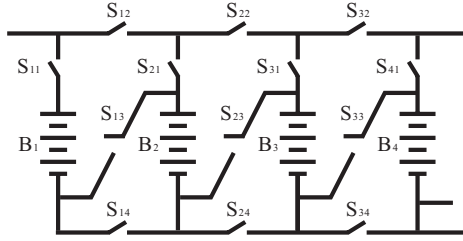


Fig. 32. Reconfigurable circuit proposed in [153].

the level of reconfigurability, as shown in Fig. 31. In particular, an SOC balancing method is proposed for the battery modular multi-level management (BM3) converter including a number of cascaded three-switch modules [149]. Each module is composed of a battery and a three-switch inverter. By properly configuring the switches, the connections between the batteries are changed and balancing is achieved.

To further improve the level of reconfigurability, each battery cell is coupled with four switches [151]–[153], as illustrated in Fig. 32. For instance, a hierarchical balancing strategy is proposed, which combines time-sharing intervention within the modules and splitting/recombination between the modules to implement balancing during the charging and discharging processes [153].

C. Reducing Number of Components

To reduce the complexity and cost of a balancing circuit, various solutions have been proposed to reduce the number of components used in the balancing circuit. For example, a switched inductor and additional switching paths are introduced to each energy storage cell in a Buck-Boost converter-based balancing circuit to implement the functionality of a multi-module Buck-Boost balancing circuit [154]. In this circuit, it is possible for a cell to charge the inductor through the switching path or to receive current from the inductor associated with another cell. Therefore, energy transfer can occur from any cell to any other cell, or from a cell in an intermediate position to the cells on both sides. While this circuit introduces additional inductors and switching devices compared to the conventional Buck-Boost converter-based balancing circuit, it requires fewer components to behave as a multi-module Buck-Boost balancing circuit. As another example, a multi-mode multi-level bidirectional converter is proposed for battery voltage balancing, which can operate multiple branches and their auxiliary circuits simultaneously to achieve faster and more selective balancing [155]. This circuit assigns a switching device and two inductors to each energy storage cell. Specifically, one inductor works with the auxiliary circuit to eliminate current circulating and reduce the switching

voltage stress while the other inductor is used for energy transfer. Moreover, a Cuk converter-based balancing circuit with a switch network is proposed [91]. Through the switch network, the two ends of the Cuk converter can be connected to any energy storage cell to implement energy transfer between any two cells.

To reduce the number of components, coupled inductors can be utilized, which are a special type of inductors that can establish magnetic coupling between multiple windings to enable energy transfer between different parts of the circuit. Therefore, they can implement various functionalities such as isolated and non-isolated transformations as well as voltage step-up and step-down conversions. Consequently, the power density of the circuit can be improved when coupled inductors are employed. For example, coupled inductors are adopted in a Buck-Boost converter-based balancing circuit for supercapacitor packs [156], [157]. By using coupled inductors instead of individual inductors, the number of switches is halved and the number of inductors is reduced. In the meantime, this circuit only requires a pair of complementary PWM signals to operate, which significantly reduces the control complexity.

D. Pack Balancing Issues

For real-world applications, numerous supercapacitors are usually connected in series and parallel to form large packs. The balancing issues for large supercapacitor packs are usually more complex. Therefore, several supercapacitor pack balancing issues have been examined. To understand the voltage unbalances of supercapacitors, a test bench is designed and implemented to characterize the voltage unbalances of a relatively large supercapacitor pack [158]. As another example, to minimize the voltage unbalances of supercapacitors before a pack is designed and implemented, the Monte Carlo rejection algorithm is employed to optimize the configuration of the supercapacitors within the pack [159]. For a general supercapacitor pack, the need for a balancing system is analyzed [160]. In particular, stochastic models of the supercapacitor parameters such as capacitance, ESR, and self-discharge current are utilized to estimate the losses of various balancing methods to facilitate developing proper balancing systems.

E. Comparison of Balancing Circuits

For the balancing circuits examined in Sections II and III, Table I summarizes their key characteristics in terms of balancing speed, efficiency, scalability, and main limitations. This comparison is qualitative instead of quantitative because these balancing circuits are custom designs in general, which means that they are proposed for specific energy storage systems in terms of application scenarios (e.g., electric vehicles and power systems), technologies (e.g., supercapacitors and batteries), and scales (e.g., a small-scale laboratory setup with a few cells and a large-scale system with thousands of cells). Therefore, it is challenging to perform a comprehensive quantitative evaluation of these balancing circuits. In fact, as the adoption of the supercapacitor technology is surging, it would

TABLE I
COMPARISON OF BALANCING CIRCUITS

Category	Speed	Efficiency	Scalability	Main limitations
Shunt resistor [29], Zener diode [33], switched resistor [34]	Low	Low	High	Energy dissipation and heat generation
Switched capacitor [47], switched LC [62]	Low-Medium	Medium	Medium	Speed depends on voltage difference
CW circuits [68]	Medium	Medium	Medium	Need external AC sources
Non-isolated PWM converters [76]	Medium-High	Medium-High	Medium	Limited flexibility
Isolated PWM converters [98]	High	High	Medium	Need more magnetic components
Resonant converters [127]	High	High	Medium	Parameter tuning process is complex
Modular circuits [137]	High	Medium-High	High	High design and control complexities
Reconfigurable circuits [140]	Medium-High	Medium	High	High design and control complexities

be of great interest if a test bench can be established to more systematically and rigorously evaluate the existing balancing circuits in a quantitative manner to facilitate developing more effective balancing solutions for different applications.

IV. BALANCING CIRCUIT CONTROL STRATEGIES

A. Distributed Control

In addition to the topology, the control strategy is another critical aspect of a balancing circuit. Therefore, this section reviews the control strategies employed in the balancing circuits.

Compared to centralized control strategies, distributed control strategies significantly reduce the communication costs. For voltage balancing, a distributed cooperative control strategy is proposed for a supercapacitor energy storage system [161]. The balancing circuit uses switched capacitors. Each supercapacitor cell is taken as an agent in a multi-agent system and the voltage balancing problem is formulated as a cooperative tracking problem. To achieve voltage balancing, each supercapacitor cell only needs the voltage information of itself and its neighbors. Consequently, a voltage balancing controller with tunable control gains is designed according to the nearest neighborhood rule and its effectiveness is demonstrated by simulations.

For SOC balancing, a distributed control strategy is proposed for a supercapacitor energy storage system [162]. This strategy employs a master-slave structure including a common voltage loop for each module and a separate slave current loop. The common voltage loop ensures that the system maintains a stable DC bus voltage and provides the same initial current reference for all modules. By introducing a universal SOC balancing bus and selecting the maximum SOC as the reference for all controllers to reconstruct the current loop, all modules operate based on the SOC to achieve balancing.

For SOE balancing, a distributed control strategy is proposed for a supercapacitor energy storage system [106]. A push-pull converter is employed to generate the balancing current during the energy transfer process when the supercapacitor operating voltage is relatively low. Based on a three-branch equivalent circuit model, the supercapacitor SOE is estimated using a Kalman filter. The balancing circuit is regulated according to the SOE deviations of the neighboring supercapacitor modules.

B. Observer-Based Control

For states (e.g., SOC and SOE) that cannot be directly measured, state observers or estimators are needed to develop control strategies for balancing systems. As mentioned in Section IV-A, a Kalman filter is used to estimate the supercapacitor SOE [106]. As another example, an extended Kalman filter is adopted to estimate the supercapacitor SOC [104]. Other observers used in balancing systems include the generalized extended state observer (GESO) [43] and the sliding mode observer [163].

C. Fuzzy Control

Fuzzy logic has also been utilized to develop control strategies for balancing systems. For example, a multi-dimensional fuzzy control (MFC) strategy is proposed for supercapacitor energy storage systems [98]. The MFC strategy uses the terminal voltage, cutoff voltage, and operating current as the input to control the duty cycle of the MOSFETs on the primary side of the transformer to tune the balancing current for each supercapacitor cell. As another example, fuzzy logic is combined with the conventional PID controller to balance a battery energy storage system [86]. Supercapacitors are used as the energy buffer in this system. The fuzzy PID controller considers the charge unbalance and the charging/discharging profile to determine the balancing current.

D. Model Predictive Control

As an effective multi-objective control tool, MPC has been explored for balancing applications. For instance, an MPC framework is proposed for a hybrid energy storage system composed of batteries and supercapacitors [50]. The proposed framework can minimize the SOC and thermal unbalances of the batteries as well as the energy losses in the balancing circuit. This work is further enhanced and a two-layer MPC framework is proposed [54]. Specifically, the first layer determines the optimal SOC reference for the supercapacitors. Based on this reference, the second layer balances the SOC, temperature, and aging of the batteries. An MPC framework is proposed to balance the aging of supercapacitors to extend the lifetime of the entire system [42].

TABLE II
COMPARISON OF BALANCING CIRCUIT CONTROL STRATEGIES

Category	Required information	Complexity	Main limitations
Distributed control [161]	Parameter measurements and limited communications	Medium	Performance might not be globally optimal
Observer-based control [163]	Parameter measurements, energy storage device models, and state estimation models	High	Performance depends on models
Fuzzy control [98]	Parameter measurements and fuzzy logic rules	High	Performance depends on fuzzy logic rules
Model predictive control [42]	Parameter measurements, energy storage device models, and state estimation models	High	Performance depends on models

E. Comparison of Balancing Circuit Control Strategies

A comparison of the balancing circuit control strategies is listed in Table II. Again, a quantitative comparison of the control strategies is challenging as the balancing systems are custom designs and a test bench is unavailable to evaluate these control strategies in a rigorous manner. Therefore, a qualitative comparison is performed instead. As for the coupling between the topology and the control strategy of a balancing circuit, a systematic and comprehensive investigation is also unavailable probably because most balancing circuits are custom designs. It is possible that a particular control strategy is adopted by different topologies. Take MPC for instance. This strategy can be used to control a switched resistor-based circuit [42] or a converter-based circuit [54]. In particular, it is claimed that the converter can be of different topologies such as Buck-Boost and half bridge [54]. In summary, the synergy between the topology and the control strategy needs to be more rigorously examined to develop more effective balancing circuits.

V. CONCLUSION AND FUTURE WORK

This paper performs a rather comprehensive review of the existing supercapacitor balancing circuits. Basic circuits based on shunt and switched resistors, Zener diodes, switched capacitors and LCs, CW circuits, non-isolated and isolated PWM converters, and resonant converters are covered. Advanced circuits including modular circuits and reconfigurable circuits are also examined. As for the control strategy, distributed control, observer-based control, fuzzy control, and MPC are summarized.

Based on this review, this paper proposes to conduct a holistic investigation of the existing and emerging topologies and control strategies of the supercapacitor balancing circuits to address the following concerns.

First, explore the feasibility of developing a general framework to facilitate rapid prototyping of proper balancing systems for a supercapacitor energy storage system with specific balancing objectives (e.g., voltage, SOC, and SOE balancing). A "proper" balancing system includes both the circuit topology and the control strategy. Clearly, to accomplish this goal, the synergy between the topology and the control needs to be investigated.

Second, if it is feasible to develop such a general framework, how the domain knowledge on supercapacitor (and battery)

balancing can be utilized. In particular, artificial intelligence (AI) for engineering has been around for a while. In the context of balancing systems for supercapacitor energy storage systems, the feasibility and effectiveness of AI-based approaches need to be investigated.

Finally, if it is infeasible (at least in the near future) to develop such a general framework, the research and development gaps need to be clearly identified and addressed. For instance, if the existing supercapacitor (and battery) balancing solutions are not sufficient to train specific AI models to develop such a general framework, alternative methods need to be developed to generate more data to train the AI models.

As elaborated in Sections III-E and IV-E, most existing balancing circuits are custom designs. Such works are valuable as they address specific balancing problems in certain applications. However, to transform these empirical works to a general framework that could help accelerate the adoption of the supercapacitor technology, more efforts need to be made.

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