

A Review on Cell Balancing Techniques and Their Complexity Levels



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Abstract With the increasing adoption of battery-based energy storage systems, especially in areas such as e-mobility and on- and off-grid energy storage applications, techniques to manage these batteries are being developed to address various application-related challenges. Battery Management Systems (BMS) are used to provide reliable protection for the connected battery pack. One of the tasks of a BMS is Cell Balancing (CB), in which the BMS tries to ensure that each individual cell or cell module has the same voltage level during charging and discharging operations. This task can become critical in applications involving Li-ion batteries, due to their sensitivity to being overcharged or deeply discharged. The complexity of a CB technique, and thus its implementation cost, depends on the battery chemistry and the sensitivity of the application. Thus, different designs with different complexity levels are being developed to address the balancing issue. This paper explores the CB techniques found in the literature in the past 20 years and categorizes them based on their complexity level. Operational and feature comparisons were carried out between the different CB designs.

Keywords Battery management system (BMS) · Cell balancing · Batteries · Energy storage

Introduction

Observing the market, it is clear that the market rules are transforming to accommodate energy storage, even when the electricity markets are heavily regulated and influenced by politics. On the other hand, emerging markets, such as EVs, provide relatively economically-safer incentives for developing technologies to be used for

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energy storage applications in general. Even when the change in the current electricity markets is slow, energy storage systems (ESSs) will provide new profit revenues by addressing challenges produced by an increased adoption of distributed renewable energy sources [1]. The chemical depreciation of batteries affects their energy density and lifespan. This chemical degradation is mainly caused by both operating the battery under a wide range of thermal conditions and subjecting the battery to frequent deep charge/discharge cycles. The SOC of a battery pack can be estimated utilizing a combination of Coulomb counting, open-circuit voltage, and the Kalman filtering technique to improve the estimations [2].

Battery management systems (BMSs) are control and protection systems used in battery module designs. In general, a BMS monitors the performance and behavior of the battery module and then controls the charging, discharging, and possibly other operations related to the operation and protection of the battery module. The main goal behind a BMS is to protect the battery module by ensuring that the module operates in safe and acceptable conditions. This protection protects the main system by ensuring the safe operation of the utilized battery and can possibly prolong the lifespan of the battery by slowing down the chemical degradation in the battery composition. Different applications of BESs can require specific requirements from the BMS, the most sensitive of which are deep charge/discharge protection, accurate state of charge (SOC) determination, and state of health (SOH) estimations [3].

In order for the battery to provide the desired voltage output, multiple cells are stacked in a series string to accumulated voltage. The reason is that designing a single standalone battery for each voltage output level is technically and financially impractical. However, the main challenge of these cell strings is balancing, since no two cells are chemically perfectly identical. Over time and after multiple charge–discharge cycles, the cells in a string will develop differences in the amount of charge they hold at a certain time (SOC) and the individual cell’s energy capacity (SOH). Therefore, cell balancing (CB) becomes the most important and sensitive role of a BMS. CB operations work on reducing the SOC differences between cells in a string. This will protect the cells from going through deep charging/discharging cycles, which protects the cells from chemical harms and prolongs and homogenize the SOH of cells [4].

Traditionally, BMSs were used in Lead-Acid battery systems to reduce the irreversible aging process on the batteries. For dynamic systems with rare stabilization periods, specific gravity and terminal voltage measurements were inaccurate; therefore, the most common method to determine the battery SOC was Ampere-hour (Ah) balancing. Attempts to calculate and the SOC of Batteries were made. An algorithm was developed to utilize the measured voltage, current, and temperature for the SOC calculations. However, the calculations were very sensitive to initial current measurement inaccuracies and thus required frequent periodic calibrations [5]. For multi-battery systems however, this was done by dividing the batteries into parallel battery strings, then monitoring and controlling each string individually so as not to lose the standalone operation capability of power supply systems [6].

Lithium Batteries are experiencing rapid adoption in the markets of both industry and consumer electronics due to their various chemistries, which can provide high

power densities, energy densities, long life span, and additional safety if managed correctly [7, 8]. With the increasing adoption of Lithium and high-temperature batteries, which are more sensitive than traditional batteries, BMSs were long expected to adopt and provide more functionalities to monitor the power flow, control temperatures, and address safety concerns. These functionalities can include data acquisition, Communication, Battery state monitoring, safety management, alongside the typical electrical management [9]. EVs demand more from a BMS, due to nature rapidly varying charge and discharge conditions as the vehicle accelerates and brakes in addition to the real-time communication with various systems present on the vehicle. Furthermore, the thermal management of batteries in EVs is relatively more challenging due to the uncontrolled and possibly harsh environments in which vehicles can be operated [10].

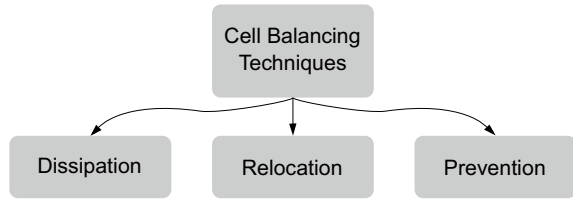
Various designs for CB techniques have been developed. The variation between these designs is the result of not only the technological advancements made over time but also the fact that different applications require different design characteristics of the CB circuit. These design characteristics are mainly balancing efficiency, balancing speed, and manufacturing and maintenance costs. Balancing speed denotes how quick the CB response is for balancing a given amount of energy over a specific time period. Efficiency, on the other hand, measures the amount of energy wasted during the balancing operation. And Finally, the cost of a given CB circuit depends on the design complexity and the used components.

This paper provides a review of the CB techniques in the literature. Older designs are included for two reasons. Firstly, to provide a context for the balancing techniques, challenges, and tradeoffs. Secondly, recent advancements in the materials and electrochemical compositions of the Li-ion batteries reduced some of the disadvantages of the older, simpler designs [11]. In addition, the paper also includes published modifications and upgrades to these existing CB designs and discusses them when found in the literature. The methodology section categorizes the CB designs into three main groups based on the criteria discussed in the section. The discussion section includes a comparison of the advantages and disadvantages of the three CB categories. Finally, the paper is concluded with our thoughts on the current literature regarding CB techniques along with future plans.

Methodology

The CB techniques can be categorized depending on the method they utilize to achieve cell balancing within a cell string. Namely, we group the CB techniques into three categories: Dissipation, relocation, and prevention. Dissipation techniques identify the overcharged cells and drain the excess energy into passive electrical elements such as resistors or power transistors. Relocation techniques divert the excess charge from the overcharged cell and store it in other cells in the cell string; the charge route is either direct or through temporary storage elements such as capacitors or coils. The prevention techniques try to predict and prevent overcharging cells

Fig. 1 Cell balancing techniques categories



before the cells actually get overcharged. Circuit illustrations are recreations from their respective cited literature. The three categories are shown in Fig. 1.

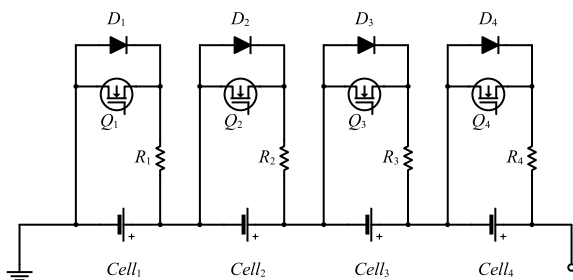
Dissipation Techniques

Shunt Resistors

This is the simplest form of cell balancing, and also the cheapest to implement. It involves using shunt ohmic resistors to dissipate the excess charge when detected on a cell in a string. This method is relatively simple to implement and cheap to manufacture. However, the excess charge is dissipated as heat through a shunt resistor. This means that the excess energy is lost rather than being relocated within the system. In addition, the generated heat will need to be removed from the system, especially in temperature-sensitive applications and/or batteries. Such designs can be found in some commercial battery systems [12]. There are two types of shunt resistor methods; passive and active. The active method is achieved by adding a switch in series with the ohmic shunt resistor to control the excess energy absorption rate [13]. Figure 2 illustrates an active shunt resistor CB circuit.

The shunting Resistor can be replaced by transistors in the common-emitter mode. This eliminates the need for a centralized controller for the series switches by using comparators to control the base of the transistor and thus control the shunt collector current [14].

Fig. 2 An active shunt resistor CB circuit



Controllable Current Sources:

The design utilizes MOSFETs connected in parallel to each cell in the string to achieve active energy dissipation cell equalization. The method is to operate gate-source MOSFETs in the saturation region where the MOSFETs behave as controllable current sources. A control algorithm is utilized to monitor the cells and identify the healthiest cell in the respective string. Healthier cells’ online determination is based on aging estimation algorithms, which in turn is decided by evaluating the capacity fade and internal resistance of the cells. Once the healthy cell is identified, the controller uses this cell’s voltage to determine the correct voltage level for the gate-sources of the MOSFETs that belong to the other cells in the string. Doing so, the voltage of each cell is changed by controlling the saturation current of its respective MOSFET, which in turn is controlled by changing the applied voltage on its gate-source.

The cell equalization is smooth and fast compared to the conventional passive dissipation methods. In addition, it is more cost-effective compared to the non-dissipative methods since it doesn’t need additional components such as converters, capacitors, and inductors to temporarily store the excess energy [11]. Figure 3 illustrates a controllable current source CB circuit.

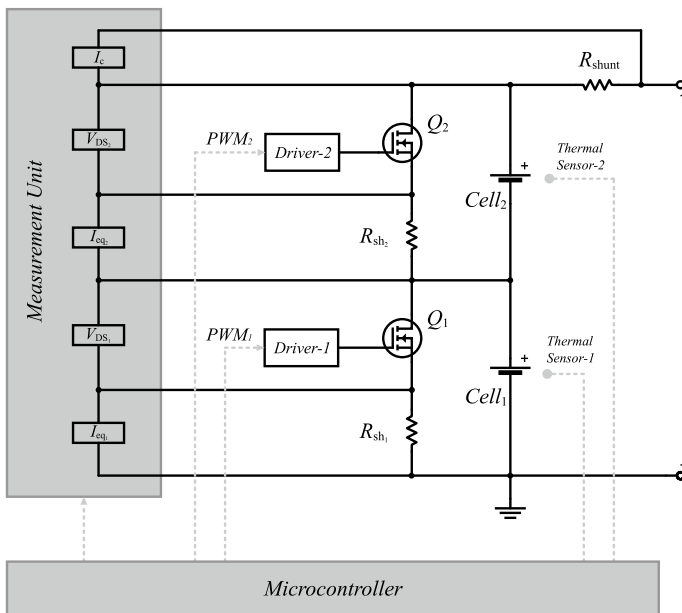


Fig. 3 A controllable current source CB circuit

Relocation Techniques

Capacitive Shuttling:

This design stores the excess charge in a capacitor and then redirects this charge to other less-charged cells in the string. In its simplest form, the design uses the switched capacitor topology, in which $2n$ switches and $n - 1$ capacitors are used to balance n cells in a string. The design is simple and cheap since it does not require a centralized intelligent controller. However, the switch count is high, and the cell equalization time is long [15]. Figure 4 illustrates a capacitive shuttling CB circuit.

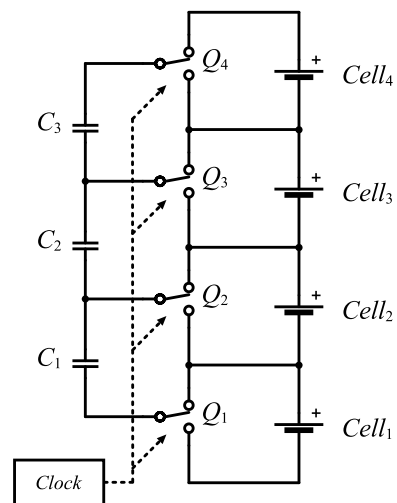
The single switched capacitor topology was developed to speed up the equalization speed by using a single capacitor for the whole-cell string. Reducing the number of capacitors reduces the size and cost of the circuit to a certain extent. However, this design does require an intelligent centralized controller to control the switches and direct the balancing currents based on each cell's condition [16].

The double-tier capacitor topology combines the previous two designs for an even faster cell equalization. Naturally, the centralized intelligent controller is still needed. Compared to the switched capacitor topology, this design can reduce the equalization time to a quarter [17].

Modularized topologies for capacitive shuttling were proposed for long cell strings. This design increases the flexibility of the equalization operation by dividing the cell string into segments and then combining these segments using additional capacitors. The main advantage is shortening the equalization times and reducing the voltages and currents of the switches for long cell strings [18].

An automatic Switched-Capacitor novel topology was developed to address the main drawback in both the switched and double-tier capacitor topologies. Namely, to allow the balancing charge to flow from the cell with the highest voltage to the

Fig. 4 A capacitive shuttling CB circuit



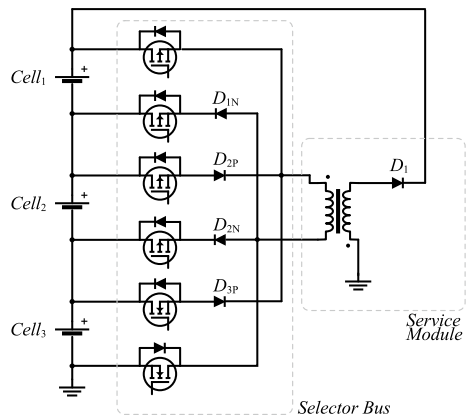
cell with the lowest voltage directly, rather than having to pass through adjacent cells first. The main advantage is to speed up the equalization process, especially for long cell strings. This design does not require an intelligent central controller, which helps keep the complexity and costs of the design low. A couple of pulse signal generators with fixed frequency and a duty ratio of 0.5 control the switches automatically. The main drawback of this design is the requirement for more switches since it requires double the number of switches found in the switched and double-tier capacitor topologies [19].

Energy Converters

Unidirectional flyback topology: The main goal of this design was to eliminate the individual cell equalizers (IECs) from individual cells and replace them with a converter for each cell string. A single flyback DC/DC converter with isolated topology is used to transfer the excess charge from a cell with a higher terminal voltage to the rest of the cell string. The path for each cell consists of MOSFETs and diodes. A digital controller in the BMS controls these MOSFET switches with PWM signals to control the current flow between the cells and the flyback converter. The design compares the cell voltage to the overall string voltage rather than the adjacent cells in the string. Thus, ICEs are not required for each cell. However, the design does require an accurate voltage sensing for each individual cell. This design is efficient for applications with a single service module; an additional higher-level controller is required for applications with multiple shared service modules. The design supports unidirectional current flow only, which forces the controller to perform the cell balancing during either charging or discharging operations [20]. Figure 5 illustrates a unidirectional flyback topology CB circuit.

Bidirectional flyback topology: This design modifies the selective flyback converter approach to accommodate bidirectional balancing current flow, which allows the balancing operation to run continuously. The used flyback converter has

Fig. 5 A unidirectional flyback topology CB circuit



two windings on its secondary side to allow two modes of operation: pack-to-cell and cell-to-pack. For 22Ah high capacity Li-ion modules, this design was simulated to reduce the average active power loss due to balancing operations by more than %50 compared to the passive shunt resistor technique. The design provides high power transfer efficiency and quick balancing times. However, the use of a transformer which increases the size and weight of the circuit. The few diodes in use and the lack of inductors help decrease the production costs of the system [13]. Utilizing a soft-switching scheme for the switches for the same design can reduce the switching losses and increase the power transfer efficiency [21].

Ramp converters: Ramp converters are used to reduce the size and weight of the circuit. In addition, the small transformer design allows for soft-switching and high switching frequencies [22].

Full-bridge converters: This design is used in high-power applications that require flexible modularity of battery packs. The design is based on pulse-width modulation (PWM) full-bridge converter while using the SOC of cells as a control method for cell balancing. The circuit provides a high degree of control, especially with the AC-DC conversion capability of the utilized converter. However, the circuit requires an intelligent controller, which adds to the complexity of the control requirements and manufacturing costs [19].

Segmentation cell-to-cell converter: This method divides the cells string into smaller segments and provides two different paths for the balancing current to flow through. One path is a buck-boost converter and is used to transfer the energy between two cells in the same segment. The second path is a flyback operation and is utilized when the two cells are located in different segments. The overall goal of the design is to allow the excess energy to pass between any two cells in the string. However, the benefit of two modes of balancing within the same cell string is to shorten the balancing paths, which leads to faster balancing operations. Planar coupled inductors were included in the design for high power density industrial applications. To ensure the accurate driving of the switches, optocoupler isolated high-density driver circuits were utilized [23].

Direct cell-to-cell converter: An improvement to the segmentation topology was proposed to avoid the segmentation altogether by allowing any two adjacent cells to exchange charge through the buck-boost operation rather than limiting this path to predefined segments. This increases flexibility and, thus, the speed of the equalization operation without increasing the complexity of the controller [23].

Center-Cell Concentration

This design tries to achieve the balancing capabilities of the bidirectional flyback designs while keeping the main advantage of unidirectional designs, namely the use of one switch per cell rather than two. Comparing this design to a regular unidirectional design, this design concentrates the charge transfer in the middle cell on a string and then distributes the excess charge to the other cells in the string upwards and downwards from the central cell. The charge is transferred to the central cell and then

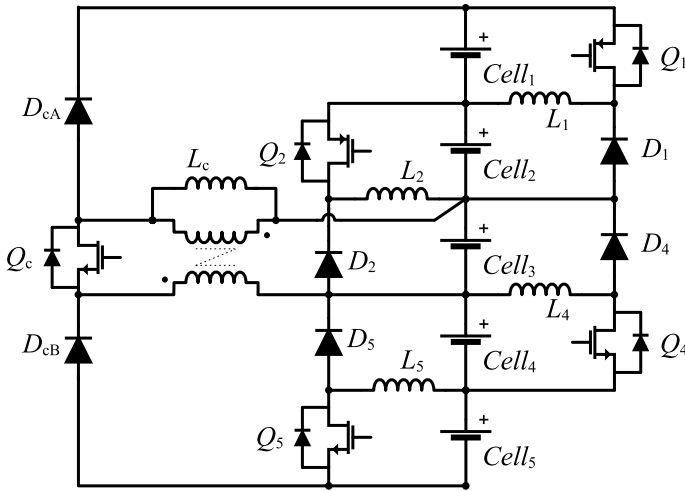


Fig. 6 A center-cell concentration CB circuit

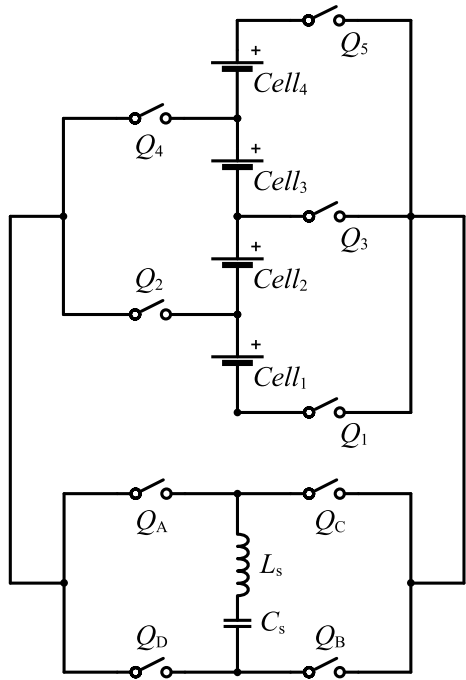
from the central cell to the other cells in the string using three buck-boost converters. The design manages to achieve balancing speeds similar to a regular bidirectional flyback design while using a single switch per cell. Reduction of the number of switches by almost half results in a considerable decrease in the size and cost of a cell balancing circuit [24]. Figure 6 shows a center-cell concentration CB circuit.

LC Series Resonant Circuit

The design utilizes an LC resonant circuit to store the excess charge from strong cells and divert it to any other weaker cell in the string and not necessarily an adjacent cell. Balancing power flow through paths controlled by bilateral switches. The design utilizes zero-current switching to reduce the power switching losses and electromagnetic interference. No auxiliary converters are required since no power sources for the gate drive is needed. As a cell-to-cell balancing circuit, an advantage of this design over the bidirectional flyback circuit is the elimination of the transformer. This allows for small-size lightweight implementations of the circuit.

A string of 12 Li-ion cells was built for the experiment. The observed power transfer efficiencies were 93.2% and 78.9% for balancing 0.56 and 1.94 W of power, respectively. 85% and 61% SOCs were balanced within 92 min, with 1.94 W of balancing power [25]. Figure 7 shows an LC series resonant circuit CB design.

Fig. 7 An LC series resonant circuit CB design



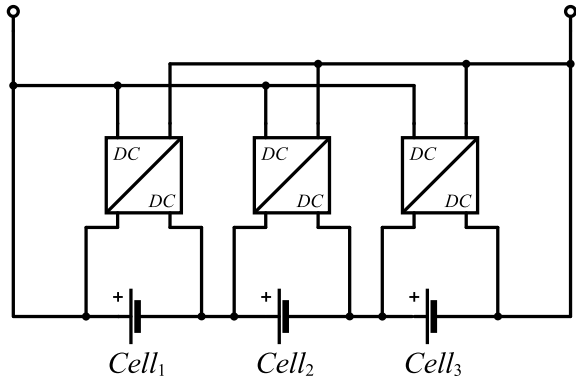
Prevention Techniques

A Converter for Each Cell:

In this design, each cell is monitored and controlled by its own DC/DC converter. Current equalization is carried out by monitoring the current of each cell, which in turn is representative of the cell’s own capacity during charging and discharging operations. Managing each cell’s current ensures that all cells in the string have the same SOC, regardless of each cell’s individual capacity. If one cell becomes incapacitated within a string, the string can continue operating in the limp-home mode, in which the string continues to produce the same voltage but with the reduced current. However, for the current equalization method to be effective, the capacities of all cells need to be estimated accurately.

Applications that utilize battery packs with short strings in addition to high-power applications can utilize this design for cell equalization since several small converters can sometimes be technically more viable than a single relatively bigger converter. Other less common applications in which cell strings consist of cells of various capacities, voltages, and chemistries can also utilize this design since each cell is monitored and controlled separately [26]. Figure 8 illustrates a converter for each cell CB design.

Fig. 8 A converter for each cell CB design



Estimation Algorithms:

This design uses a typical flyback equalizer in the pack-to-cell mode. However, the decision to start the balancing is taken before the voltage or SOC imbalances actually happen. The main goal is to predict which cell is on its way to be deeply charged/discharged. This is done by estimating the relative capacity of each cell while utilizing the power to energy ratio. Rather than comparing actual quantitative values, the algorithm monitors the rate of charging or discharging of each cell and compares it to the individual cell’s power to capacity ratio. For the algorithm to work properly, the total energy capacity must be known, and all the series-connected cells having the same SOC versus open-circuit voltages curves are assumed. A drawback in this design is the lack of consideration of cells’ initial SOC differences, which can have a negative impact on the balancing speeds. In addition, the power balancing circuit is capable of handling a limited balancing current [27]. Figure 9 shows the flyback equalizer used in the algorithm-driven CB design.

Decentralized Smart Cells:

Am more complex design for managing each cell individually is the concept of smart cell modules with internal standalone decentralized control. The main advantage here is the modularity of cells that can have different capacities and usage histories. Thus, the SOC of the cells is synchronized by loading the healthier cells more to make the degradation of the cells in the string more uniform. Each smart cell has a local controller, sensing equipment, and switching networks to monitor and control the cell. The design at hand uses a microcontroller that uses a series inductor to sense the voltage and then control the duty cycles of a half-bridge switching network [28]. Figure 10 shows a decentralized smart cell CB design.

Fig. 9 The flyback equalizer used in the algorithm-driven CB design

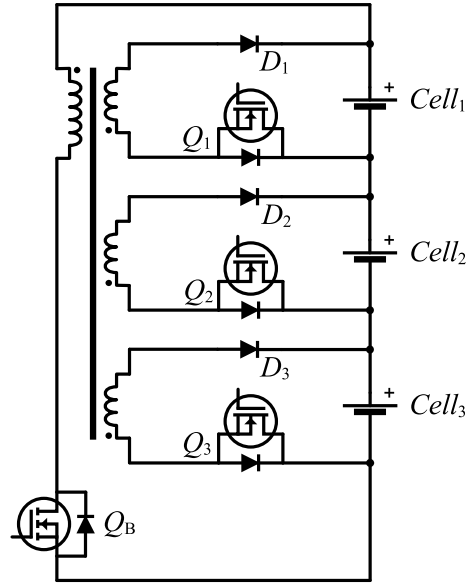
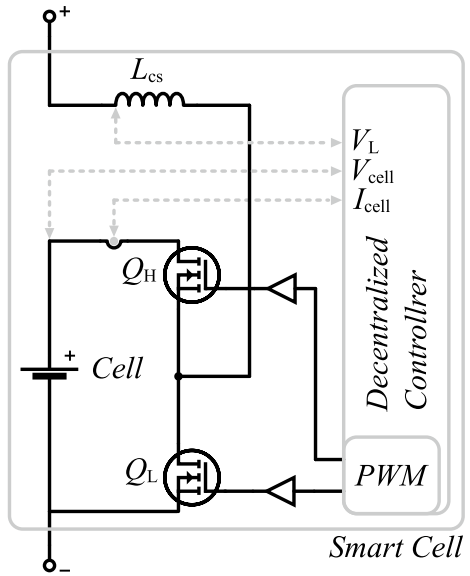


Fig. 10 A decentralized smart cell CB design



Discussion

Comparing the operational differences between the three categories, it becomes clear that dissipative techniques are simpler and cheaper, preventive ones are more complex and expensive, and relocation techniques sit somewhere in between.

Dissipative designs might look primitive, have limited functionality, and suffer some balancing energy losses. However, recent advancements in the materials and electrochemical compositions of the Li-ion batteries reduced some of the disadvantages of these older and simpler designs in terms of balancing efficiency and speed. Furthermore, these simple designs' lightweight nature provides an important advantage in applications where weight considerations are a priority.

The prevention methods are used in applications where the battery pack performance and lifetime longevity are relatively more important than the financial considerations. Cells will inevitably degrade and lose capacity over time. Therefore, in applications where replacing the degraded cells has relatively high logistical costs, investing in such designs reduces the operational costs of such systems in the long run. This becomes more viable when we take into consideration that such cell balancing techniques have the ability to manage and control each cell at its individual optimum, which in turn prolongs the effective lifespan of the cells and reduces the frequency of cell replacements.

Relocation designs try to strike a balance between the other two categories. Usually, the proposed designs focus on a certain aspect of the balancing operation and improve on it. The aspect of focus can be balancing speed, efficiency, or cost. Since different applications have different requirements and limitations, focusing on the priority aspect of the design is technically and financially more viable. The flexibility of these designs is their strength and advantage from a design point of view. This is the reason these designs are more diverse and common among the three categories. The main disadvantage of these designs is their reliance on additional components such as capacitors, coils, and converters, which in turn add their own weight and intrinsic power losses to the CB design.

Conclusion and Future Work

In this paper, we discussed the principles of cell balancing for cells in a series string. We reviewed the literature for CB designs for the past 20 years. The designs were categorized into three groups depending on their balancing method; Dissipation, Relocation, and Prevention. The advantages and disadvantages of each design were discussed for each design. Furthermore, updates and modifications to the reviewed designs were also included in their respective section for added clarity on the design progression over time. Each design proved its usefulness in certain applications by matching the application requirements and limitations. Some designs gained usefulness with recent advancements in the electrochemical compositions of the batteries,

which was driven by the recent increase in the adoption of Li-ion batteries in various applications. The increasing pace of both BESSs adoption and battery chemistry development will require an equal pace for developments in the CB designs. Developments in CB include both developing novel designs and exploring new applications for older designs.

For the future, we intend to perform simulation performance comparisons between these designs in light of both the addition of new CB designs and advancements in battery designs and performances.

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