Next-Generation Battery Management Systems: Dynamic Reconfiguration

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Batteries are widely applied to the energy storage and power supply in portable electronics, transportation, power systems, communication networks, etc. They are particularly demanded in the emerging technologies of vehicle electrification and renewable energy integration for a green and sustainable society. To meet various voltage, power, and energy requirements in large-scale applications, multiple battery cells have to be connected in series and/or parallel. While battery technology has advanced significantly in the past decade, existing battery management systems (BMSs) mainly focus on state monitoring and control of battery systems packed in fixed configurations. In fixed configurations, though, the battery system performance is in principle limited by the weakest cells, which can leave large parts severely underutilized. Allowing dynamic reconfiguration of battery cells, on the other hand, allows individual and flexible manipulation of the battery system at cell, module, and pack levels, which may open up a new paradigm for battery management. Following this trend, this paper provides an overview of next-generation BMSs featuring dynamic reconfiguration. Motivated by numerous potential benefits of reconfigurable battery systems (RBSs), the hardware designs, management principles, and optimization algorithms for RBSs are sequentially and systematically discussed. Theoretical and practical challenges during the design and implementation of RBSs are highlighted in the end to stimulate future research and development.

I. Functionalities and Benefits of Reconfigurable Battery Systems

RBSs, conceptually, are capable of changing the battery interconnection pattern in response to the battery behavior, state of controllable hardware components, and user demands. Fig. 1 illustrates a set of application scenarios of RBSs. The enabled functionalities and potential benefits are summarized as follows.

1) Enhanced Fault Tolerance: In a conventional battery system, the configuration is generally fixed once deployed. Faults of a cell, such as internal and external short circuits, may not only damage the cell but may also rapidly spread to its neighboring cells and gradually destroy the entire system. This will directly waste the energy, materials, and investment in the neighboring cells, and the local cell-level faults can potentially escalate to higher levels and cause fires and explosions, leading to catastrophic consequences to the battery-powered devices as well as their users. These risks can be avoided by an appropriately designed BMS equipped with dynamically controlled configurations. Specifically, RBSs are able to quickly disconnect the faulty cells while reconnecting the remaining normal ones [6–10]. This means that local faults can be isolated timely so that other cells can keep working normally without significantly affecting the system-level functionalities and performance. Fig. 1 (a) uses a simple battery structure designed in [11] to elucidate the fault isolation in RBSs. The malfunctioning cell (C_2) can be bypassed by manipulating the switches around it while other normal cells can continue providing power to the load or absorbing energy from the charger.

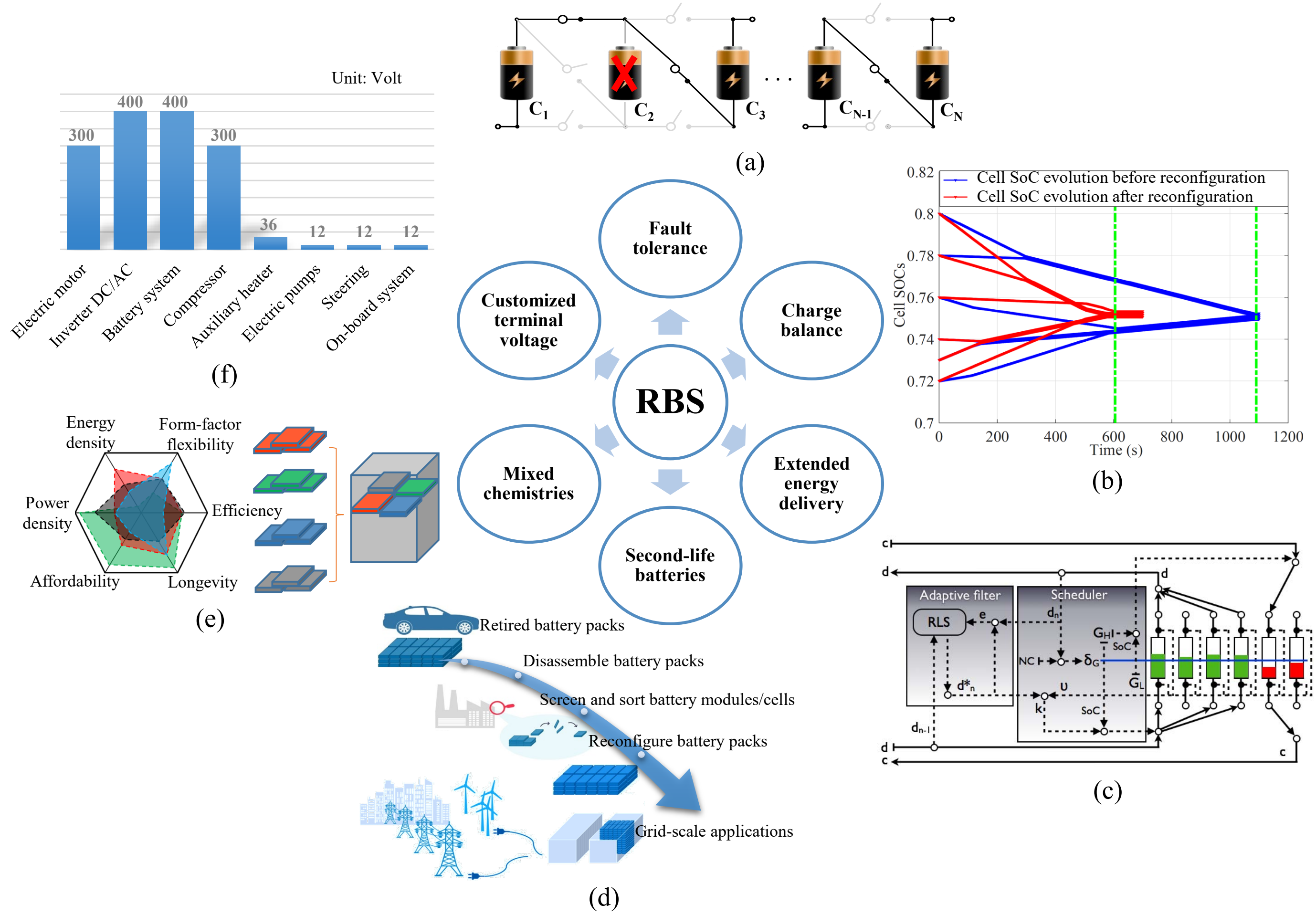


Fig. 1. Typical functionalities and benefits of reconfigurable battery systems (RBSs). (a) Faulty cell isolation. (b) Expedited charge equalization for battery cells [1]. (c) A scheduling framework proposed in [2] for extended energy delivery and operation time. (d) Coordination of second-life batteries (revised from [3]). (e) Mixed battery chemistry (revised from [4]). (f) Component voltage levels in electric vehicles [5].

2) Charge and Temperature Balancing: Due to inevitable variations in manufacturing and different operating conditions, battery cells of the same type in a pack are inherently heterogeneous, which can be reflected by unbalanced charge and non-uniform temperature. The charge imbalance largely reduces the available charge capacity of series-connected multi-cell systems. Under this circumstance, some cells will be underutilized, leading to unnecessary up-front cost, weight, and space [12], while others may encounter overutilization, such as overcharging and overdischarging, being the primary reason for premature battery degradation [13] and safety issues [14]. The thermal imbalance will cause different cell aging rates and reduce the longevity of the battery system, as well as potentially trigger overheating and threat battery safety.

To address the inconsistency in battery systems with fixed configuration, charge balancing circuits and cooling devices have to be added into the BMS [15–17]. Fortunately, through the system reconfiguration, the battery charge equalization process can be substantially expedited. This can be clearly evidenced in Fig. 1 (b), where after reconfiguration only about half of the time is needed for cells to reach the state of charge (SoC) equalization [1]. Notably, for RBSs cell balancing is possible to achieve without any additional balancing circuitry. For instance, by changing the configuration, cells with larger SoC can be charged at lower currents or for a shorter period. Similarly, temperature gradients can be effectively flattened by coordinating the cell current.

3) Extended Energy Delivery: Motivated by the idea of battery balancing without auxiliary balancing modules, the dynamic reconfiguration can also be used to schedule the operation of batteries for faster and enhanced energy conversion during both charging and discharging. Taking the charging of a series of battery cells for example, such benefit can be realized by sequentially putting cells at rest once they have reached the upper voltage limit. Then, the charging rate of cells below this limit does not have to be lowered down due to those already hitting the limit. As a result, if the current and temperature are controlled precisely, all cells can be charged to their full capacity more rapidly. For the discharging process, appropriately scheduling the operation and rest of batteries could also improve the conversion of the battery chemical energy into electrical energy. A design of such a scheduling framework is illustrated in Fig. 1 (c) [2] for extended energy delivery and operation time, where the arrowed solid lines c and d represent the charging and discharging currents, respectively. By scheduling the battery operation, substantial potential to increase the total energy delivery was also demonstrated in [18, 19].

4) Coordinating Batteries of Different Age or Chemistry: Once manufactured, batteries continuously experience aging under storage, charging, and discharging due to a number of side reactions, as reviewed in [13]. The irreversible aging process causes a decrease in the charge capacity and an increase in the internal ohmic resistance. While the former shrinks the battery energy capacity, the latter degrades the battery power capability. Because of manufacturing variation and the long-term unbalanced distribution of SoC and temperature, battery cells in a pack commonly suffer from different levels of aging, and the health of those most aged cells will determine the system's lifespan. In turn, inconsistent health levels will also immediately affect SoC and temperature profiles across the in-pack cells. Therefore, as compared to battery charge balancing, the management problem becomes more complex for batteries of different ages. In practice, battery cells with less than 80% of their rated capacity are considered to no longer suit EV applications [20], but may still keep a huge value for stationary energy storage where operating conditions are more gentle and requirements on energy density are less strict [3, 21]. With the intrinsic merit to balance batteries, RBSs cannot only prolong the first-life usage but also become imperatively important for second-life applications as shown in Fig. 1 (d).

The dynamically reconfigurable structure is also beneficial for managing battery cells of different chemistry. The initial idea was proposed in [4] and the technology was referred to as software-defined batteries (SDBs), as illustrated in Fig. 1 (e). SDBs are motivated by the fact that different commercial batteries perform better in different aspects, such as energy density, power density, lifespan, cost, fast charging capability, and energy efficiency, making them apt to different applications. The goal of SDBs is to fully employ the strengths of different types of batteries through dynamic reconfiguration.

5) Customized Terminal Ranges: Fig. 1 (f) lists the nominal voltages for electric components in medium-size passenger EVs. Clearly, the voltages demanded by different components span a large range. If the traction battery system needs to provide energy for all these components, a set of inverters and converters are required, implying increased cost, weight, and system complexity, and reduced energy efficiency. An RBS is capable of customizing the terminal voltage, current, and power in a wide range. Thus, inverters and converters used for connecting the battery system with electrical components can be avoided. Likewise, the voltage range of chargers to recharge RBSs can be largely extended, which, accordingly, increases the convenience for EV charging.

6) Other Benefits: The reconfiguration technique makes it viable to share battery modules and packs among different applications, enabling a new battery business model not otherwise economically justifiable, and further enhancing the economy- and resource-efficiency. This can involve cells of different SoC, temperature, age, type, and chemistry, i.e., completely different cells even within one pack. Moreover, thanks to the reconfigurability, battery cells and modules in an RBS may be separately diagnosed, repaired, or replaced, requiring much lower maintenance efforts and costs as compared to working on an entire battery pack with a fixed configuration. Many battery types should not be stored at the fully discharged level, and, consequently, a battery system with a large number of cells connected in series becomes difficult and dangerous to handle due to the high voltage and high energy. However, in an RBS, where cells can be flexibly disconnected, this complicating issue, can be completely avoided.

7) Summary: The functionalities and benefits of RBSs discussed above are all attributed to the added freedom to redistribute battery current offered by dynamic reconfiguration of battery cells, modules, and packs. Thus, not only those aforementioned, all current-related performance metrics can be potentially improved or even optimized via appropriate battery system reconfiguration enabled in a next-generation BMS. This will ultimately and significantly boost the system-level performance, such as the lifespan, fault tolerance, energy utilization efficiency, charging speed, power capability, and convenience of batteries.

II. Analysis of RBS Circuit Designs

Generally, battery system reconfiguration can be implemented in two ways, namely relocating battery cells/modules/packs or altering their connection/wiring. In the vast majority of commercial applications, battery cells, modules, and packs are assembled in a way not allowing physical movement because of safety and reliability concerns. Furthermore, the average cost to change the position of batteries, in practice, can be prohibitively high. In this regard, research and development efforts of RBSs have been mainly devoted to changing the connection/wiring topologies.

To design an RBS, auxiliary circuit devices are imperative. Switch circuits, possessing the capability of directly disconnecting and reconnecting individual batteries, have become the most popular option. The existing switch circuits are either mechanical or semiconductor-based. Mechanical switches can be implemented by relays with single contact, changeover contacts, or multiple contacts sharing one actuator [22]. The advantages of such switches are that they are capable of performing both forward and reverse current control. However, mechanical switches are prohibited from parallel connection since too large current may pass one contact if some switches react faster or slower than others [23]. Unlike mechanical switches, semiconductor switches, such as metal oxide semiconductor field effect transistors (MOSFETs), demonstrate good performance when connecting battery cells in parallel. Because of this, MOSFETs of low cost and high conduction efficiency have been applied to many emerging designs of RBSs. Comparative discussions on implementing these switch circuits can be found, for example, in the thesis [22] and the survey article [24].

The number of switches assigned to each battery cell and their connection pattern determine the system's reconfigurability. A number of circuit designs for RBSs in the literature [2, 6–11, 25–35] are illustrated in Fig. 2, where two to six switches are connected to each battery cell to realize various connection and operation possibilities. These circuit structures are further compared in Table I in terms of the number of switches per cell, achievable connections and operations, and the reported advantages over traditional battery systems. For notational convenience, S (P) is used to indicate the series (parallel) connection of battery cells. SP (PS) indicates that cells can be connected in series (parallel) to form a module and that the obtained modules can be connected in parallel (series). The underline of S (P) indicates that any cell/module connected in series (parallel) can be individually bypassed. The hat under S (P) indicates that cells/modules connected in series (parallel) can be bypassed but in companion with others. The subscript "1" of S (P) indicates that only one module can have multiple cells connected in series (parallel). Based on these circuit designs in Fig. 2, the following benefits have been claimed by these RBSs relative to their fixed-configuration counterparts: (i) enhanced fault tolerance and operation safety, (ii) improved energy efficiency, (iii) more balanced system operation, (iv) increased charge delivery/storage and longer operating time, (v) prolonged battery lifespan, and (vi) customized terminal voltages.

Several observations can be made from Fig. 2 and Table I. Designs (a)-(d) are focused on connecting all battery cells in series, and any cell is allowed to be bypassed/isolated by associated switch operations. By expanding each cell in design (a) to a module, the design (e) is obtained, in which parallel cell connection is attainable but still restricted within a local module. In designs (f) to (k) with at least three switches per cell, all battery cells are possible to be connected in series, parallel, or more complex ways. For example, the cells can get connected in series (parallel) at first to form a module, and the modules are then connected in parallel (series). To test various possible connections and operations, as well as to develop reconfiguration strategies, a prototype of the RBS design (f) is carried out by H-bridges in our

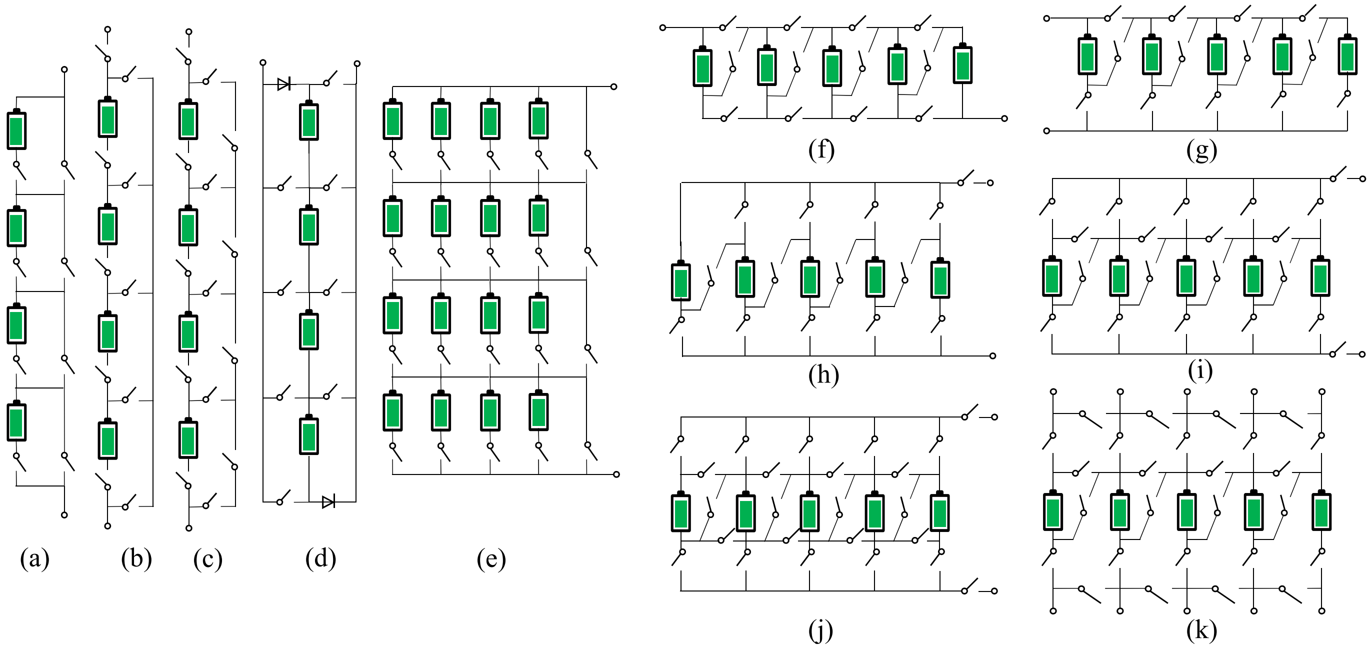


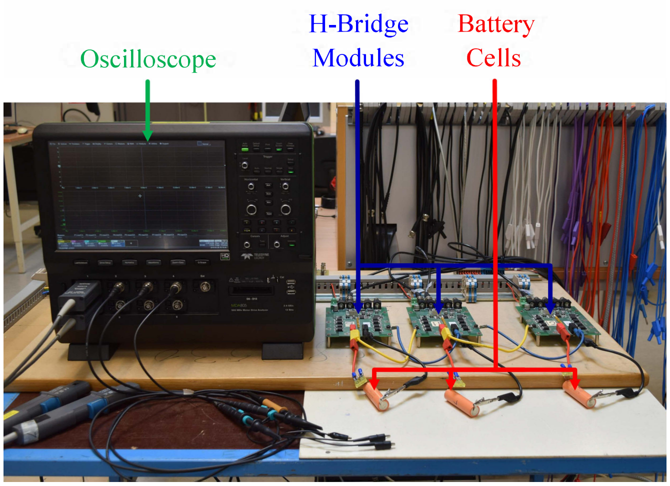
Fig. 2. Illustration of various RBS circuit designs proposed in the recent literature.

TABLE I
COMPARISON OF VARIOUS CIRCUIT DESIGNS OF RBSS ILLUSTRATED IN FIG. 2.

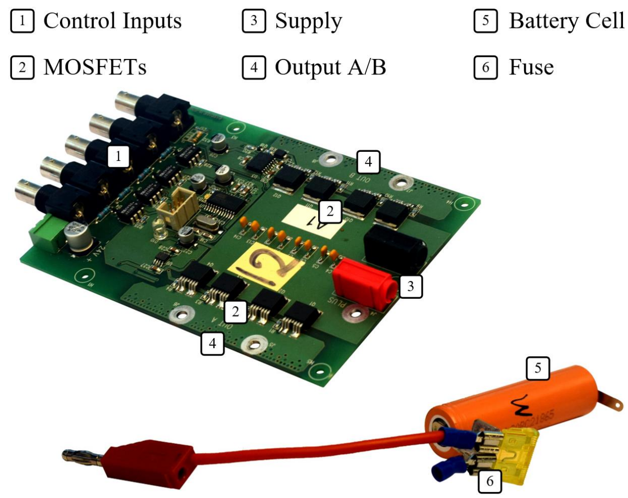
Design diagram	Reference source	Switches per cell	Connections and operations	Reported benefits
Fig. 2 (a)	[26, 27]	2	S	(i), (ii), (iii)
Fig. 2 (b)	[25]	2	S	(ii), (iii), (iv)
Fig. 2 (c)	[10]	3	S	(i), (iii), (iv), (vi)
Fig. 2 (d)	[28, 29]	2	S	(i), (iii)
Fig. 2 (e)	[9, 30]	1∼2	PS	(i), (ii), (iii)
Fig. 2 (f)	[11]	3	S, P, PS	(ii), (iv)
Fig. 2 (g)	[36, 37]	3	S, P, P_1S, S_1P	(i), (iii), (v), (vi)
Fig. 2 (h)	[31, 32]	3	S, P, SP	(ii), (iv)
Fig. 2 (i)	[6, 33, 38, 39]	4	S, P, P_1S, SP	(ii), (iv), (vi)
Fig. 2 (j)	[7, 34]	5	S, P, PS, SP	(i), (iv)
Fig. 2 (k)	[2, 8, 35]	6	S, P, PS, SP	(i), (iii), (iv), (vi)

battery lab, as illustrated in Fig. 3. When at least five switches are assigned to each battery cell, e.g., via the designs (j) and (k), battery cells can be reconfigured flexibly among the S, P, SP, and PS connections and any cell can be bypassed if requested.

It is worth noting that even using the same number of switches per cell (e.g., three switches per cell applies to the designs (c), (f), (g), and (h) in Fig. 2), we can achieve very different connection topologies, depending on how these switches are connected to the cell. Thus, not only the number of switches per cell but the way of switch-cell connection also contributes to the system reconfigurability. In addition, the system complexity and overall cost of RBS circuit designs depend heavily on the number of switches. To design scalable RBSs and retain the same freedom for cell control, the same number of functional switches and the same way of connecting should be applied to all battery cells (except those located on the boundaries). This will effectively reduce the complexity of system design, mathematical modeling, and control algorithms for the RBS management.



(a)



(b)

Fig. 3. A prototype made by three battery cells connected through three H-bridges, according to the RBS design in Fig. 2(f). (a) General setup. (b) H-bridge and battery cell.

By carefully comparing and analyzing various reconfiguration designs, it can be found that the switches around each battery cell can be divided into different groups to realize specific connections, such as series connection, local parallel connection with neighboring cells/modules, global parallel connection of all cells/modules, and bypass connection. These switch groups can operate independently, exclusively, or jointly with each other. Grouping switches based on achievable connections will shed some new light upon the design of RBSs. Then, per the request of system reconfigurability, one can actively select the corresponding groups of switches and estimate the total number of necessary switches for cost assessment.

III. Management Principles of Battery System Reconfiguration

The various circuit designs of RBSs analyzed above pave the way for pursuing a number of potential benefits, of which some have been reported in Table I. Once the RBS circuit design is carried out, appropriate management strategies need to be developed, with the goal to identify and realize the configurations yielding the desired system performance. To do so, the management principles for battery reconfiguration under different scenarios are discussed in this section.

8) Principle for Fault Isolation: For continuous and safe operation of RBSs, it is crucial to isolate any faulty, overcharged, or overdischarged battery cell without interrupting others. This functionality has been widely applied in RBSs [6–10, 26, 28, 30, 40]. While battery isolation or skipping can be realized in most RBS designs in Fig. 2 (indicated by the underline of connections in Table I), different switch operations may be performed, depending on the circuit designs. When battery cells are connected in parallel, e.g., the design (e) in Fig. 2, it is easy to skip a cell by operating only one switch. If the cell to be isolated lies in a series-connected cell string, e.g., designs (a)-(c) in Fig. 2, at least two switch operations need to be conducted simultaneously. To isolate a cell in RBSs with more switches per cell and mixed series/parallel connections, e.g., designs (f)-(k) in Fig. 2, sufficient care should be taken to coordinate multiple switch operations so that no open and short circuits are incurred.

9) Scheduling Principle for Charge Balance: In addition to passively skipping faulty battery cells, RBSs can tackle the charge imbalance by actively scheduling the operation tasks of normal batteries. Aimed at more balanced operation, the basic principle of such battery scheduling is to periodically prioritize the charging (discharging) of battery cells with lower (higher) charge. To do so, the first step is to sort all battery cells according to the amount of charge which, unfortunately, cannot be physically measured. Thus, different alternatives are applied to the battery sorting, e.g., the cell's SoC [2, 9, 18, 27, 41, 42], open circuit voltage (OCV) [25], and terminal voltage [19], in which the former two are usually used in combination with state estimation.

After the sorting, in response to the total charging/discharging demand, battery cells are selectively put into use following the above principle for balanced operation. Note that, the battery sorting should be periodically or adaptively updated according to battery state dynamics. As a result, the charge levels of battery cells can gradually get balanced, and meanwhile performance improvements arising from the charge balance can be achieved.

10) Scheduling Principle for Enhanced Energy Conversion: Appropriate battery scheduling can also help deliver more energy or charge during discharging, corresponding to a higher conversion efficiency from the battery's chemical energy to electrical energy. To accomplish this, the reconfiguration principle can be derived based on the recovery effect of batteries, i.e., the battery's terminal voltage at discharging can quickly recover if it is allowed to rest for a while or discharge at a lower current rate [2, 10, 18]. The voltage recovery is mainly determined by the battery SoC, discharging rate, and the scheduled operating and resting time. To take advantage of this effect, a simple scheduling principle was developed in [18] for discharging a battery system consisting of four battery packs. The general principle is to periodically detect and rest the battery pack of the lowest charge while continuing discharging the others. Following this, the total energy delivery, from fully charged level to completely discharged level, can be extended as compared to the case when all packs are always discharged without any scheduled resting. For a quantitative investigation, the extended energy deliveries under different constant load power levels and resting periods are identified and compared in Fig. 4, based on experimental test data gathered from [18].

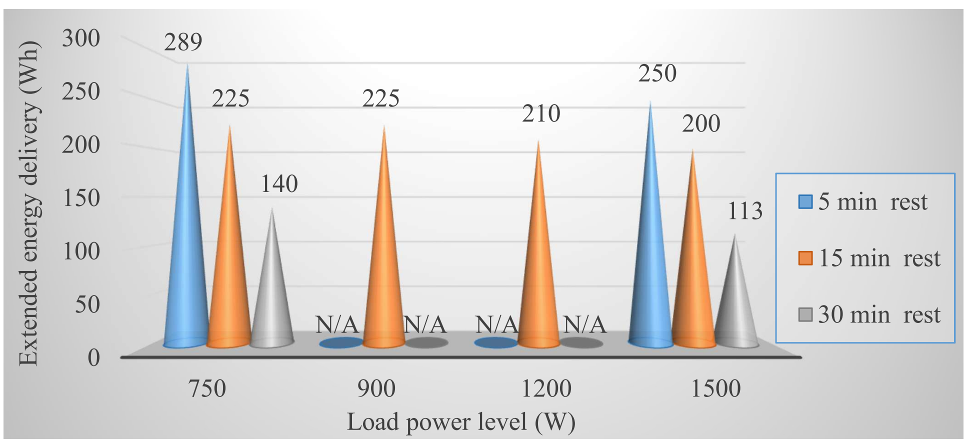


Fig. 4. Comparison of the extended energy delivery at various load power levels and scheduled resting periods for a battery system composed of four reconfigurable battery packs. Note that zero resting time corresponds to zero extended energy delivery by definition.

It can be seen from Fig. 4 that the total energy delivery can be increased in all the tests. Given the same resting period, the extension demonstrates a decreasing trend in response to increased load power, e.g., the four orange cones with a resting period of 15 minutes. Such influence of load power level arises from the battery rate-capacity effect, i.e., the higher the discharging rate, the lower the charge/energy delivery [2, 10, 38, 43, 44]. Thus, when choosing the group of batteries scheduled to rest, a trade-off has to be made between the resting batteries' recovery effect and the operating batteries' rate-capacity effect. This was discussed in [27] and quantitatively examined in [2]. In addition, as illustrated in Fig. 4, the scheduled resting period imposes a significant influence on the extended energy delivery. The majority of battery voltage recovery can be achieved very quickly, e.g., within one minute for battery packs in [18], and, consequently, additional resting time of the lowest-charge pack does not contribute much to the recovery. However, a longer resting period corresponds to a longer operating period and larger voltage drops for those operating packs, which makes it easier for them to hit the lower voltage limit. Therefore, when designing the scheduling principle for extended energy delivery, appropriate resting and operating periods should be carefully selected based on the requested load power level. The total energy delivery under a wide range of resting periods was also experimentally tested and compared in [19], indicating that it is possible to maximize the total energy delivery under certain resting period.

11) Principle for Improving Circuit Energy Efficiency: The energy efficiency of an RBS depends on not only the battery energy conversion discussed above but also the energy loss of all circuit components involved. The switch circuit plays an essential role in battery system reconfiguration. Its power loss includes losses in the MOSFET switches and the gate drive circuits. The former are composed of conduction and switching losses, and the latter depend on the specific gate drive circuit design. For instance, for the switch circuit design in [9], as the discharging current increases, the total power loss of switch circuits decreases at first and then increases. Thus, there exists a discharging current leading to the maximum power efficiency of the switch circuits. In addition, the RBS enables a flexible and wide-range system terminal voltage, and the load/charger voltage can also change over time. To buffer the voltage mismatch between the RBS and the load/charger, voltage regulators or power converters are needed, which introduces additional power conversion losses [11, 31, 33, 43]. Such losses of voltage regulators can vary dramatically. As pointed out in [31], the conversion efficiency can actually drop below 50% at light load conditions. The regulator's efficiency is dependent on its input voltage, i.e., the RBS terminal voltage [11, 31]. Thus, in pursuit of higher efficiency of these circuit components, the common practice is to first evaluate the efficiencies of these components at various voltages and currents, and then comprehensively select the configuration placing the operation in the high-efficiency operating range of these circuit components while meeting the charging/discharging requirement in real time.

12) Additional Principles: Other principles of battery system reconfiguration can also be developed. For example, principles for faster charge equalization by analyzing performance evaluation formulas can be found in [1, 45], and principles for distributed control based on consensus protocols have been presented in [29, 46]. These heuristic RBS management principles are aimed to achieve a more robust, balanced, and efficient system operation. However, the optimal performance of RBSs may not be attained unless equipped with advanced optimization and control algorithms, as detailed in the next section.

IV. RBS Modeling and Optimization Algorithms

In order to maximize the benefits of RBSs while ensuring safety and reliability, optimization algorithms need to be developed. To do so, the fundamental step is to develop the mathematical model of RBSs.

A. Modeling of RBSs

In an RBS, battery cells, switches, and their interconnection topology all influence the performance significantly. Therefore, it is necessary to establish mathematical models capable of accurately predicting the evolution of critical system states.

There are three general classes of battery cell models, i.e., physics-based, equivalent circuit-based, and data-driven. As mentioned before, a vast number of battery cells can be involved in large-scale RBS applications. How to mathematically model such complex systems, from cell to module and pack level, with a good balance between computational efficiency and accuracy is a key problem. Physics-based models have been widely studied in academia to describe internal dynamics of a lithium-ion battery cell, including ion diffusion and intercalation/de-intercalation processes. Based on the porous electrode theory and concentrated solution theory, the initial model was proposed in [47], consisting of a set of partial differential-algebraic equations (PDAEs). The PDAE-based battery model was reformulated and simplified, e.g., in [48, 49], to facilitate cell-level simulation and control applications. However, to apply physics-based models to BMS, further efforts are still needed to reduce the complexity of computation and parameterization.

With the advent of the big data era, data-driven battery models have recently become popular. Up to date, the main research focuses of such models have been on data-based prediction and estimation of the battery SoC [50], state of health (SoH) [51], and remaining useful life (RUL) [52]. Equivalent circuit-based models (ECMs), on the other hand, are relatively simple to parameterize and implement in battery pack control [53], and, hence, are preferred in today's BMS designs. The primary drawback of ECMs is the lack of physical insights directly relating to battery safety and health, such as the local overpotential and the solid-electrolyte interphase (SEI) film.

To model a battery system with multiple cells connected in a fixed configuration, a simple and widely applied industrial practice is to view the pack as one virtual cell. Specifically, the cell-level model is still used but the model parameters are identified based on the pack behavior [54]. In an RBS, since both series and parallel battery connections can be flexibly reconfigured, each battery cell has to be individually modeled to adapt to different system configurations. At the same time, modeling each cell will facilitate characterizing the cell-level imbalances in terms of charge [55], impedance, and capacity, analyzing the cell current distribution under various system configurations, and finally designing proper RBS optimization and control algorithms. These benefits are, however, achieved at the cost of dramatically increased model complexity.

Switches are essential components to enable the reconfigurability of battery systems and can be realized through different circuit elements. In switch modeling, the connection changes are of course most important, but the electrical and thermal characteristics during conduction, in general, are also important. MOSFET switches outperform mechanical ones in terms of much lower power demand for actuation and better synchronization for parallel connections [22]. For the MOSFET switches, one important parameter is the drain-source on-resistance, normally denoted by $R_{DS(on)}$ and defined by the total resistance in the conductive path from source to drain when the MOSFET is turned on. $R_{DS(on)}$ consists of a series of sub-resistances and demonstrates high dependence on the real-time junction temperature, drain current, and gate-to-source voltage [56–58]. As a result, it becomes challenging to model the exact dynamic behavior of switches. In some studies, for simplicity, $R_{DS(on)}$ is simply ignored [25] or assumed constant [37]. However, accurate switch modeling is still worth exploiting when $R_{DS(on)}$ is comparable with the internal resistance of battery cells and imposes considerable influence on the total resistances.

The remaining task is to model various interconnections of battery cells through switches. A natural way to describe the interconnection of battery cells and switches is by a graph representation, a state vector, or a state matrix. For instance, consider the small RBS in Fig. 5, the system configuration, composed of only cell 1 and cell 3, can be represented by either the edge information in a graph, i.e., $\mathcal{E} = \{n_+ \rightarrow c_1, c_1 \rightarrow c_3, c_3 \rightarrow n_-\}$, a cell state vector (c_1, c_2, c_3) = (1,0,1), or a switch state vector $(s_1, s_2, \ldots, s_8)$ = (1,0,1,1,0,1,1,0), where 0 and 1 indicate the disconnected and connected states, respectively.

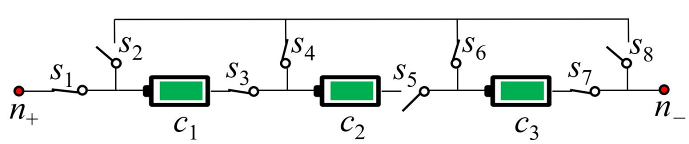


Fig. 5. A three-cell reconfigurable battery system based on the design in Fig. 2(b).

Finally, the entire RBS can be modeled by wrapping up all component models. Given any specified system configuration of the RBS, the open-circuit elements are deactivated, and the electrical interaction among the remaining active battery cells and switches is characterized following Kirchhoff's current law (KCL) and voltage law (KVL). Such an RBS model will act as the basis for model-based performance optimization in the subsequent subsection.

B. Optimization Algorithms based on Reconfiguration

To date, only a few studies have been conducted to improve the RBS performance using model-based optimization algorithms. The common goal of these studies is to identify the system configuration yielding the best performance.

Table II summarizes the optimization problems of battery reconfiguration in recent literature. In these problems, the total charge/energy delivery (storage) during discharging (charging) or the power/energy loss has been regarded as the objective function. Other benefits arising from battery system reconfiguration, such as speeding up the charge balancing [1, 45], are also possible to quantify and maximize. The above objective functions are often subject to three types of constraints to ensure safe and efficient operation of RBSs:

- Electrical and thermal constraints enforced on batteries and switches to guarantee their operations within appropriate ranges of current, voltage, power, and temperature. Most constraints in the referred works in Table II fall into this type.
- Constraints on the system configuration, e.g., assigning the same number of cells to each string [11].
- Constraints on the sequential or synchronized switch operations to avoid any circuit faults.

TABLE II
SOME OPTIMIZATION PROBLEMS OF RBSS FORMULATED IN RECENT LITERATURE.

Sources	Objective function	Constraint	Method or Algorithm
[25]	Minimize the total additional resistance	Charging current and No. of cells per string	Graph theory based method
[11]	Minimize the total power loss during one control period	System configuration, switch operation, battery bank voltage and current	Looking up tables prepared offline
[33]	Minimize the discharging current of individual cells	Terminal voltage range	Graph theory based method
[43]	Maximize the deliverable charge capacity	Each cell belongs to one and only one string	Graph theory based method
[34]	Minimize the total charge consumption	Terminal current and voltage	Lagrangian relaxation and dynamic programming
[38]	Maximize the charge delivery during discharging	Total load power	Dynamic programming and genetic algorithm
[42]	Minimize the total energy loss during charge balancing	Total energy delivery and No. of cells applied	Dynamic programming
[44, 59]	Minimize the total capacity loss	Battery cell states, load profile, and working conditions	Lagrangian relaxation and dynamic programming

Among the problems in Table II, those formulated in [11, 25, 33, 43] focus on only one period, either the present control period or a full discharging process. To solve such optimization problems, graph theory has been deployed based on the graph representation of system configurations. For example, minimizing the total additional resistance was transformed to a minimum path cover problem in [25], and maximizing the battery pack's charge delivery was achieved by constructing and solving a maximum-weight independent set problem [43]. In [11], the power loss curves and terminal voltages of different system configurations were evaluated offline in advance and subsequently used for determining the optimal configuration online in response to the voltage and current demands.

When it is desired to optimize the overall system performance across successive control periods, as in [34, 38, 42, 44, 59], the system evolution over these periods has to be considered, such as the time-varying OCVs, SoCs, and total available charge or energy of the cells. To take this into account, a dynamic system model has to be appended to the optimization problem as a constraint. Such an optimization problem can be regarded as a typical optimal control problem, where some performance goals can be accomplished by applying variable constraints. For instance, in order to achieve charge balance eventually, the charge difference among battery cells is forced to zero at the end of the last control period [42].

Basically, the formulated optimal control problems can be solved either numerically, for example, using Bellman's dynamic programming (DP), or analytically, using Pontryagin's maximum principle [60].

The problems proposed in [34, 42, 44, 59] are all solved by DP, a common tool for solving multi-stage optimization problems. When solving these optimal control problems formulated for RBSs, the computational time and memory requirements are influenced by a number of factors, such as the system dimension, model nonlinearity, number of feasible configurations, and control horizon. Consequently, online applications of these optimal control methods easily become infeasible for large-scale RBSs and/or long control horizons. To reduce the computation burden, an alternative optimization problem with respect to load power classes instead of successive control periods was constructed in [42] at the cost of sacrificing the global optimality of the original problem. In general, the real-time applications of optimal control to RBSs are still at a preliminary stage. There still exist some challenges in formulating appropriate RBS optimization problems with detailed expressions of objective functions and constraints and developing computationally efficient algorithms to solve them.

V. Challenges and Outlook

While system reconfiguration promises to bring various benefits toward advanced battery management, several critical challenges still need to be addressed during the hardware design, algorithm development, and switch operations.

A. Hardware Design

In the phase of hardware design, both the system structure and the corresponding components need to be determined. During this process, a number of design factors have to be comprehensively considered, including the requested functionalities, specific constraints on the entire RBS, and the rating of all electrical components involved.

When designing battery systems with a fixed configuration, the series and/or parallel connection structure of battery cells can be quickly determined according to constraints on the entire system, e.g., the ranges of terminal voltage and current, the required power capability, energy capacity, and lifespan, as well as the limits of space and weight. However, to seek the desired functionalities and benefits of RBSs, e.g., charge balancing and enhanced energy delivery, a new task is to identify the RBS structure candidates supporting them. This task initiates the design of RBSs but has never been systematically studied so far. Some clues can be found in Table I based on the association of various design structures with their enabled connections and operations. Further research efforts are expected to guide the structure selection for achieving various potential benefits of RBSs.

Another task is to choose appropriate components, such as batteries, switches, sensors, and cables, so as to fit into the candidate RBS structures. Well-designed sensing and fault tolerance mechanisms along with associated hardware resources also need to be in place to tackle the faulty parts and to protect the remainder. Since a large number of interconvertible configurations can be enabled in an RBS, the rating of all electrical components and the fault tolerance design have to be performed for all feasible configurations under various working scenarios. This can become very time-consuming for large-scale systems and leaves a challenging research gap in the RBS design. Future investigation should be aimed at first identifying an appropriate set of desired and feasible configurations by prohibiting those potentially unsafe or unnecessary ones. Then the rating of various components can be focused on these selected configurations under corresponding working conditions.

Furthermore, the rating of components can be extended to cover the RBS's high-efficiency operating conditions, and high-quality or redundant components can be deployed to improve the reliability. These, however, normally contribute to an increased total cost, which is an important concern in the RBS design. Thus, a trade-off has to be made between the system efficiency, reliability, and total cost. Although such a trade-off is also necessary for designing battery systems of fixed configuration, it becomes more complicated in designing RBSs due to much more operating scenarios and components. A preliminary attempt has been made for battery pack sizing in [61], where the overall cost of cells, sensors, and controllers was analyzed and reduced while providing the required power and reliability. Following this thread, it is important to develop a generic framework in the future to strike a balance among all design factors of concern.

B. Development of Optimization Algorithms

After setting up the selected RBS hardware design, the system performance can be optimized by manipulating its configurations. To develop such optimization algorithms, the system configuration is viewed as the decision variable, i.e., the cell interconnection is not deterministic. Consequently, circuit laws are difficult to apply to model the system operation, and the objective function generally lacks an explicit dependence on the system configuration. These two aspects make it challenging to formulate the optimization problem as a detailed analytical expression.

Due to the above features and the imposed state constraints, gradient-based methods cannot be directly applied, and, thus, numerical methods have to be deployed. Given any possible and feasible system configuration, a battery system model can be constructed accordingly, and the resulting system performance can be evaluated by simulation or analytical expressions [1, 45]. Then, the best performance along with the corresponding configuration can be identified by exhaustive search if the system dimension is relatively small, or by heuristic algorithms, such as genetic algorithm. Such performance evaluation and searching can become very time-consuming for large-scale systems with a huge number of possible system configurations, and the globally optimal configuration cannot be guaranteed. For instance, to evaluate the minimum charge equalization time of a reconfigurable battery series with 15 cells by exhaustive search, the average computational time is estimated to be over two years [45]. Therefore, when applying these numerical search methods to RBS performance optimization, substantial attention should be paid to the computational efficiency, especially for online applications within a BMS.

C. Switch Operations

Once the desired system configuration is determined for the established RBS, the original configuration will be converted to the desired one through a set of sequential and/or synchronized switch operations. These switch operations should be well coordinated for efficient implementation but without causing any short circuit or unintended open circuit. Ideally, all switch operations involved can be performed simultaneously to directly set up the desired configuration. For example, in order to isolate cell c_2 in Fig. 5 without interrupting other cells, both connecting switch S_5 and disconnecting switches S_4 and S_6 should be executed simultaneously. In practical reconfiguration, however, switch operations may not be well synchronized due to control signal delays and/or hardware limitations. This can cause undesired transient system behaviors, e.g., high transient current endangering the related components. Such practical issues must be carefully addressed by accurately modeling the dynamic behaviors of all interconnected components. However, this is still a challenging task due to limited modeling fidelity of components and substantial simulation time.

Moreover, when performing sequential switch operations in RBSs, certain time delay is required between every two successive operations. The more sequential switch operations, the longer the reconfiguration time. As a consequence, some urgent actions, such as isolating the faulty cell, might be delayed, incurring serious safety issues or hardware damages. For such systems, heuristic suggestions are given in [61] on reducing the reconfiguration time, such as limiting the reconfiguration within a small area and reducing the number of battery packs to be reconfigured. Additionally, as demonstrated in [18, 19, 61], the frequency of reconfiguration also influences the RBS performance, e.g., total energy delivery, and the optimal frequency is possible to be identified through a large number of experimental tests [19] or simulations based on high-fidelity models. Despite these preliminary explorations, comprehensive guidelines for safe and efficient reconfiguration in complex and large-scale RBSs are still absent.

VI. Conclusions

Compared to fixed configurations, dynamic reconfiguration of battery systems at pack, module, and even cell levels, has great potential to improve the system performance from many aspects, e.g., fault tolerance, energy utilization, fast charging, and lifespan. Motivated by this, BMSs with the freedom of dynamic reconfiguration open up a new path to enhanced energy storage and conversion in various applications, including electrified vehicles and power grids. This article provides a critical and comprehensive overview of RBSs. After analyzing a variety of circuit designs for RBSs, we devoted the majority of efforts to the principles for managing RBSs and the algorithms for optimizing their performance. Several critical challenges in the RBS hardware design, algorithm development, and switch operations have been identified and discussed. To address these challenges, future research and development directions were highlighted. In view of fairly scarce resources in the current literature for systematical and comprehensive studies of RBSs, this article is intended to inspire innovative thinking from both researchers and engineers on present designs and to motivate more advanced reconfiguration technology toward the next-generation BMSs.

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