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# Reconfigurable Battery Techniques and Systems: A Survey

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**ABSTRACT** Battery packs with a large number of battery cells are becoming more and more widely adopted in electronic systems, such as robotics, renewable energy systems, energy storage in smart grids, and electronic vehicles. Therefore, a well-designed battery pack is essential for battery applications. In the literature, the majority of research in battery pack design focuses on battery management system, safety circuit, and cell-balancing strategies. Recently, the reconfigurable battery pack design has gained increasing attentions as a promising solution to solve the problems existing in the conventional battery packs and associated battery management systems, such as low energy efficiency, short pack lifespan, safety issues, and low reliability. One of the most prominent features of reconfigurable battery packs is that the battery cell topology can be dynamically reconfigured in the real-time fashion based on the current condition (in terms of the state of charge and the state of health) of battery cells. So far, there are several reconfigurable battery schemes having been proposed and validated in the literature, all sharing the advantage of cell topology reconfiguration that ensures balanced cell states during charging and discharging, meanwhile providing strong fault tolerance ability. This survey is undertaken with the intent of identifying the state-of-the-art technologies of reconfigurable battery as well as providing review on related technologies and insight on future research in this emerging area.

**INDEX TERMS** Reconfigurable battery pack, energy storage system, SOC, battery management system.

## I. INTRODUCTION

The increasing demand for replacing fossil fuel with electricity and the growing market share of electronic vehicles (EV) have led to a new area of academic research and industrial design, where the battery system is expected to be safe, cheap, and efficient with a long lifespan [69], [70]. For example, Chevrolet [3] and Tesla Motors [4] have produced EVs using several hundreds and several thousands of battery cells, respectively. Besides of being used in EVs and hybrid electronic vehicles (HEV), large-scale battery systems are also widely adopted in grid energy storage systems, backup power systems, and other energy storage related applications.

Conventionally, multiple battery cells are encased in battery packs in an ad hoc way, where battery cells are connected into a fixed series-parallel cell topology to fulfill voltage and current requirements. However, there are several major deficiencies in traditional multi-cell battery systems. Since these fixed cell topologies cannot adapt the dynamic behavior of battery cells and manufacture difference, cell unbalance issue always exists. In practice, as battery packs are charged and discharged repeatedly over time, each battery cell shows different characteristics; especially one or more weak cells will be charging or discharging faster than others. Therefore, weak cells will limit the operation cycle life of the entire pack or even cause severe safety issues, such as burning and explosion due to thermal runaway and overheating [1]. Fixed topology also has a limitation on management: no active management can be implemented due to lack of flexibility, which leads to a series of problems including over-charge and over-discharge.

The defects in traditional battery pack designs highlight two main problems in battery powered devices: exhaustion of the scarce energy and low energy conversion efficiency due to poor system ability. As a result, large-scale reconfigurable battery packs and corresponding battery energy management systems (BMS) emerged as a promising solution to overcome these defects [2]. A typical reconfigurable battery system is illustrated in Figure 1, where cell level topology can be modified to accommodate cell characteristics and load efficiently. This ability is achieved by deploying power switches around battery cells and adjusting cell connectivity in a real time fashion. Beside high energy-density battery cells and switching circuit, a well-designed reconfigurable multi-cell battery pack also requires an efficient BMS to cope with nonlinear battery characteristics and load demand.

A basic requirement of a BMS is that it should be capable of bypassing any cell as well as adjusting the configuration of cells according to real time operational conditions, such as cell status and load profile, while keeping a balanced cell states across the entire battery pack. This task is challenging because even if the initial states of cells are identical, with the increment of the charging-discharging cycles, cells tend to show different characteristics, and some cells become weaker than the others, which is usually known as cell-to-cell unbalance problem [12]. In a fixed cell topology, a weaker cell is more likely to be over-charged and/or over-discharged, which, in turn, would accelerate the aging process and make the weak cell even weaker. Finally, the weak cells would become faulty quickly and cause the entire pack to be dysfunctional.

A high performance BMS should be designed not only to handle cell-to-cell unbalance problem, but also to provide accurate estimation of the status of the battery cells in the pack, as well as maximize energy efficiency and safety. Currently, BMS designs can be categorized into two basic types, namely flat and modular. In the former type, one control module is in charge of all components, which makes it easy to be implemented with a relatively low cost on hardware elements. However, this type of architecture is not scalable since the complexity and latency grow rapidly as the number of circuit elements increase. The fault tolerance ability, energy efficiency and reliability of this type are questionable as well. Modular architecture, in contrast, is a distributed scheme where an individual control module is only in charge of one subset of elements [5]. Higher monitoring efficiency and energy efficiency can be achieved by applying this distributed scheme. However, the cost of components is much higher compared with the flat type of BMS systems.

Several synergetic integrations of BMSs and switching circuits have been put forward to maximize system performance and reliability with the minimum cost [6]. Two main challenges are supposed to be considered carefully during the development process of reconfigurable battery pack. Firstly, there is a tradeoff between the maximum reconfigurability and the minimum circuit elements usage. For a given reconfigurable battery pack, the topology can be abstracted into a graphic representation, where nodes stand for battery cells, and paths represent switches. In this way, the study of reconfigurability becomes an investigation of the connectivity and reachability of a graph. It is obvious that more switches around each cell will lead to better reconfigurability. However, at the same time, the cost and the complexity in hardware and management increase. Furthermore, controlling more switches requires more complex operation and controller area network (CAN) protocol, which increases the software burden as well. Secondly, a reconfigurable architecture should be specified with the corresponding software and hardware to achieve the maximum performance and reliability. Furthermore, the cell topology and the corresponding BMS should be oriented to applications as well. A well-designed reconfigurable battery pack is supposed to combine hardware and software to provide scalability, reliability and cost-effectiveness.

In this paper, a comprehensive survey on existing reconfigurable battery pack designs is provided. As far as we know, this is the first work that offers a full review of the technological in this area. We aim to identify the state-of-the-art technologies of reconfigurable battery packs as well as providing background knowledge and insights for future research. The rest of this paper is organized as follows. Challenges and hazarders in battery pack design are described in Section II. Section III presents the related techniques. Topology and management of existing designs are described in Section IV. Section V introduces how reconfigurability can assist charging. Section VI talks about battery management systems for reconfigurable battery packs. Latest applications and outcomes are presented in section VII. And Section VIII concludes the paper.

## II. TECHNICAL CHALLENGES IN BATTERY PACK DESIGN

The ability of matching cell parameters with specific load profile is fundamental for reconfigurable battery system design [7]. In practice, safety issues are critical and required to be taken into considerations as well. In cell level safety, the dominating factors of inherent cell safety are cell chemistry and internal structure, which are determined by manufacturers. Designers mainly focus on pack level safety to avoid shorting, malfunction, and abuse. In this section, an overview of challenges that reconfigurable battery packs faced with is represented. We start by challenges inherited from traditional multi-cell pack design, and then provide challenges unique to reconfigurable battery packs.

### A. CIRCUIT SAFETY

Circuit safety issues are critical for all circuit designs, especially the power supply system such as battery based energy storage systems. Among all circuit safety issues, short circuit is acknowledged as one of most serious problems. A short circuit is referred to as an abnormal connection between two nodes of an electric circuit, which may generate current thousands times larger than the intended operational current, causing ohm heating of circuit elements, and is a common cause of fire.

The worst case of short circuit may lead to formation of an electric arc that can produce large amount of heat and result in ignition of combustible substances. Short circuit and overcharge experiments were reported in literature [10], where X-ray was used to facility observation of structural destroy. The results show that battery cells can be easily destroyed in short circuit occasions. Immediately after short circuit, currents in the range of 102 A to 183 A are measured, which are extremely high for battery cells. The observed structural breakdown includes safety valves opened, leakage of electrolyte, and metal containment broken. Note that the experiments in [10] were done with single cells in a relatively large space; the situation could be more severe if short circuit happens in narrow space such as inside reconfigurable battery packs where hate dissipates slower.

Short circuit may happen in any electronic devices, however, reconfigurable battery packs are more vulnerable to it compared with traditional pack designs. Besides potential design defect, current loop that connect anode and cathode directly can be formed by malfunction of switching circuit, followed by catastrophic consequences [11].

Circuit breakers for equipment (CBE) are vital to protect circuit from damage. Traditionally, electromechanical designs such as circuit breakers, relays, contactors, and power switches have been widely adopted to fulfill the goal in the past 100 years. In recent years, solid state power switching designs have been gaining increasing amount of attention as a promising technique in modern circuit design. Solid state power switches have much higher voltage drop compared to mechanical contacts, which leads to a need for heat sinks for power dissipation. As a result, extra space and weight budget are required than the semiconductor itself. Since no physical isolation that equivalent to air gap in a mechanical contact exists, off state in a solid state power switch is not a clean cut off from power. These drawbacks are getting more and more trivial with the development of highly efficient semiconductors like SCR, MOSFET, and IGBT. The most prominent advantage of deploying these semiconductors is safety since no mechanical moving exists and no arcing is generated during power switching. Meanwhile, these switches can last up to millions of cycles. However, a comprehensive design or design principle of protection circuit for large scale reconfigurable battery pack is still not provided in literature. This problem can be solved in the future with the development of battery pack design propelled by increasing market share of EVs.

### B. THERMAL ISSUE

Unlike circuit safety issues such as short circuit that can destroy entire battery pack within short time period, thermal issues tend to cause damage in a long-term fashion, since circuit elements are exposed in an improper thermal condition and lifetime compromised. Abnormal thermal condition will intensify cell-to-cell imbalance and also reduce cell lifetime tremendously. An extreme case of thermal issue is named thermal runaway, where an increase in temperature of an overheated cell breaks thermal balance which releases energy from other battery cells and in turn further increases temperature. The most common causes for thermal runaway in traditional battery pack are improper charging or discharging behaviors that generates more heat in battery pack than it can be dissipated [8]. As will be presented in the following subsection, reconfigurable battery packs have higher risk to suffer from thermal runaway due to the amount of heat generated by switching circuit. Once the thermal equilibrium is disturbed, more intensified electrochemical reactions could be triggered inside battery cells leading to an even higher temperature. As a result, battery cells are literally 'running away'. If the situation is allowed to continue, the entire system may experience gassing, pack rupture, dry out, fire, or even explosion [8].

In fact, thermal issuesexist not only in battery packs used in EVs, power grids, standby power systems, and data centers, but also in our daily life. Batteries from HP, Toshiba, Lenovo, Dell, Apple, as well as other manufacturers were called back because of fire and explosions just a few years ago [9]. Reports on exploding cell phone are still occasionally seen in newspaper today. As mentioned previously, the dominating determinants of cell safety are chemistry and construction. For lithium-ion battery with high power density, one easy solution is using safer and less reactive anode and cathode materials, and non-flammable electrolytes. Furthermore, thermal management is required to eliminate the potential of this problem in battery pack by keeping an even and apposite thermal condition across battery pack by dissipating extra heat.

### C. EFFICIENT SENSING

Due to hazardous given above, as well as divergence of cell characteristics and time-varying load demand, large-scale reconfigurable battery packs must be monitored carefully, periodically, and accurately [64]. For example, The cell voltage monitoring circuit must be very accurate to allow a full charge while preventing an overcharge [56]. It is obvious that higher sensing rate, deploying high-quality hardware components will lead to better sensing results. However, it is not practical under most circumstances. First of all, the cost of large amount of high-quality sensors itself is already a problem. On the other hand, measured data from cheaper sensors introduce errors, which is misleading for state estimation and decision making modules. Taking SOC estimation as an example, when Coulomb counting method is adopted, erroneous current measurement will result in drifting of SOC value and this drafting error accumulates over time. The situation for voltage-based SOC estimation can be even worse in short term for some specific types of lithium-ion battery with flat OCV-SOC curve over SOC range of [0.2, 0.8], where 1% error in voltage measurement leads to up to 20% SOC estimation error [60]. Second, applying more hardware components will result in higher failure rate. Higher monitoring frequency imposes higher computation and communication load, thus intensifying this problem as well. Furthermore, in a large-scale monitoring system, the limitation on the number of digital I/O lines is also a dominant concern [59]. A well-designed sensing circuit for a large-scale reconfigurable battery system is supposed to jointly consider cost, circuit design issues, fault tolerance under various environments, as well as influences introduced by noisy sensor measurement.

### D. PASSIVE COMPONENTS IN RECONFIGURABLE BATTERY PACK

Passive components refer to all the parts within the system that have no contribution to the energy or power density. Choosing proper passive components during design process is challenging, which requires a comprehensive understanding of battery characteristics, circuit features, fault tolerance, as well as other design parameters. In reconfigurable battery pack design, passive components such as switches, fuses, and pre-charge circuits have critical influences on system parameters like weight, cost, volume, and safety.

Sizes of switches and fuses are strongly dependent on the current and rises rapidly as current value goes higher. This is also true for other components such as cables and bus bars. The influence that passive components have on reconfigurable battery pack can be serious since countless of them are deployed. One case study in [55] shows that weight of switches and related elements count for 8% of the total weight of entire system. This value can be even higher if better reconfigurability is required. Besides weight and wiring issues, heat emitted from switches is also a critical problem. All other components will be influenced if the heat is not released properly, which will lead to sensor measurement error and battery aging fast. If reconfigurable battery packs have to be built in a sealed off environment, designers must consider how the heat can be dissipated to avoid severe consequence such as thermal runaway as introduced in the previous subsection.

## III. RELATED TECHNIQUES IN RECONFIGURABLE BATTERY PACK DESIGN

Although challenges and hazarders exist, reconfigurable battery packs still catch attentions from industrial companies and academic organizations because of its flexibility and efficiency. Typical reconfigurable battery packs are integrated by multiple parts that cooperate together, including battery cells, switching circuit, embedded management modules, and so forth. As a result, techniques from multiple research areas are required. In this section, we present an overview of key techniques that are involved in multi-cell battery pack design.

### A. SINGLE CELL BATTERY

As the foundation of any battery pack design, numerous types of batteries have been designed and manufactured, including lead-acid, zinc-bromine, zinc-chloride, zinc-air, iron-air, nickel-cadmium, sodium-sulfur, lithium-iron, lithium-ion, and so forth. Each one of these types is unique in chemistries and inner structure, and provides specific benefits in terms of longevity, price, energy density, maximum output power, and so on. In this subsection, two of the most frequently used types will be introduced.

#### 1) LEAD-ACID BATTERY

The usage of lead-acid battery can be dated back to late 1850s [65]. They are most commonly used in automobiles because of the large power-to-weight ratio and the low price. The output power can be quite non-linear, and the lifespan depends hugely on the load profile. Compared with other batteries technologies, one distinct disadvantage of lead-acid batteries is the relatively lower energy density, so that the lifespan tend to be short. As a result, there is a trend to use them as emergency power backup.

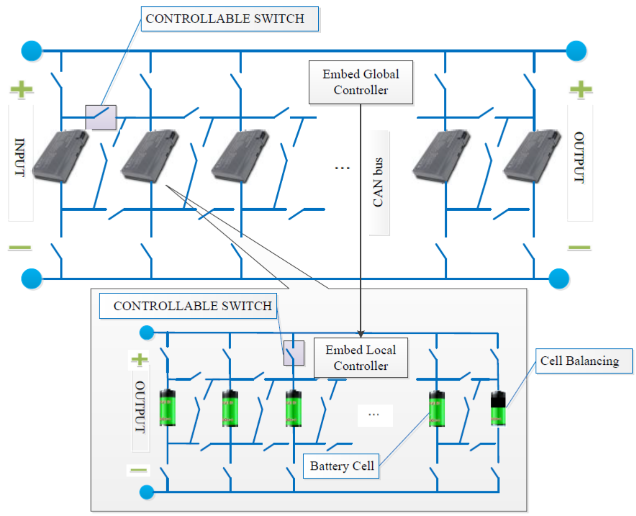


**FIGURE 1.** A diagram of typical large-scale reconfigurable battery pack design.

#### 2) LITHIUM-ION BATTERY

First commercialized in 1991, lithium-ion battery is one of the newest battery technologies, which is generally acknowledged as the most promising technique because of its high energy density, long cycle life, low self-discharge rate, and no memory effect [66]. One obvious drawback is that lithium-ion battery is far more expensive compared with batteries in almost any other kind. However, lithium-ion battery is still one of the fastest growing markets and research areas for energy storage and EVs.

### B. CELL BALANCING

After choosing one specific type of battery cells for large scale battery pack design, designers will have to face a notable problem named cell unbalance issue, which usually appears as divergence in open-circuit voltage levels and SOC values. This cell state divergence always exists after repeatedly charging and discharging over a period of time. According to previous research [13], the causes of cell unbalance can be categorized as internal source and external source. Internal sources include manufacturing variance between each battery cell and different initial state of charge (SOC), etc. External sources mainly include circuit design defects, imperfect battery state estimation and management mechanism, and thermal condition difference across the battery pack.

The cell unbalance issue prevents battery pack from supplying full capacity or being fully charged, thus degrading

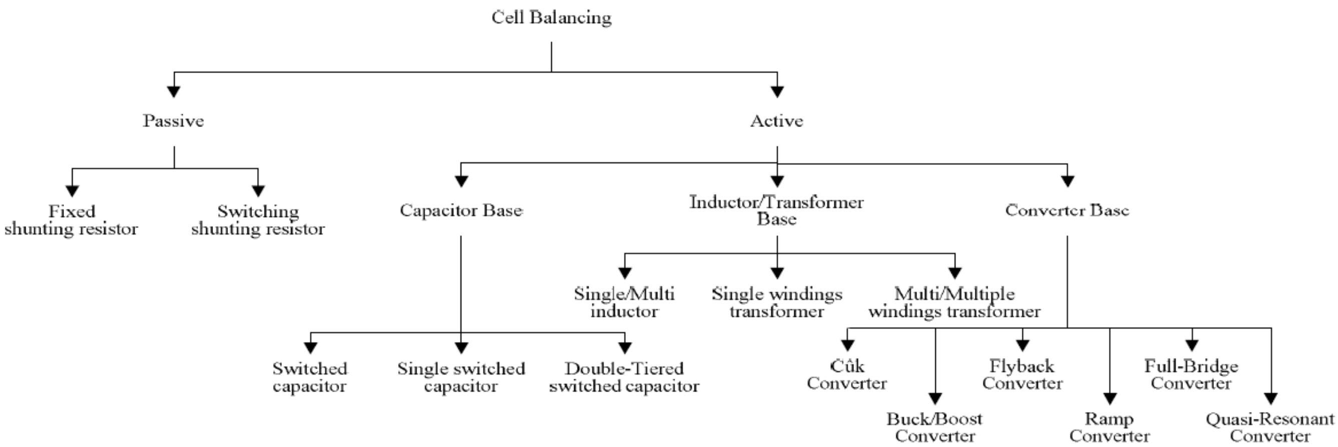


**FIGURE 2. Classification of cell balancing technologies.**

the system performance significantly especially for series connected scenarios, where the lifespan is determined by the weakest cell. Furthermore, unbalanced cell states may cause safety issue due to overheat and thermal runaway. As battery packs in EVs gets larger and rate capacity of each cell increases, more efficient methods of charge equalization are required to manage and control cell unbalance condition of a large number of battery cells. Moreover, equalizers require auxiliary control circuits for cell balancing. In literature, numbers of balancing technologies have been proposed and validated to solve the cell to cell unbalance problem. As illustrated in Figure 2, traditional balancing technologies mainly fall into two categories, namely passive and active balancing [13]. In the passive balancing methods, excess charge is removed through fixed or switching resistors to ensure that voltages of higher cells in the pack match those of lower cells [24]. The advantages of passive methods include easy implementation, smaller volume occupied, lower cost, and easy to control. However, excess charge is dissipated as heat, resulting in low energy efficiency and also intensifying thermal problem. Moreover, number of circuit elements and current value in balancing current is limited under a certain threshold in passive scheme to avoid the overheat problem, thus a long balancing time is required due to low balancing current. In active cell balancing, charge is extracted from stronger cells and goes to weaker cells, thus higher energy efficiency can be achieved with higher hardware cost and management difficulty [30]–[32]. A detailed comparison is given in Table 1 [13].

Cell-to-cell unbalance issue still exists in reconfigurable battery pack, and can be solved by techniques given in Table 1. However, there is one more choice for reconfigurable battery pack to solve cell unbalance problem, since cell level connection in reconfigurable battery pack can be adjusted in real-time not only according to load demands as in traditional battery packs, but also based on battery characteristics [56]. As a result, lifespan can be extended and cell-to-cell balanced condition becomes achievable without extra

**TABLE 1. Comparison of cell balancing technologies.**

| Scheme | Advantages | Disadvantages |
|---|---|---|
| Fixed/Shunting Resistor | Cheap, simple to implement | Not very effective, relatively high energy loss |
| Switched Capacitor | Simple control, low voltage stress | Relatively low equalization rate |
| Single/Multi Inductor | Fast equalization speed | Switches current stress |
| Single/Multi Windings Transformer | Fast equalization speed, suitable for EV and HEV | High cost, high control complexity |
| Buck-Boost/Fly -back/ Ramp Converter | Good equalization speed, ideal for transportation applications | High cost, high control complexity |

balancing circuit. The theoretical basis of this balancing method is shown in [57], where load currents are shared among cells with unequal SOC. Whenever cells with different SOC values are connected in parallel to the load, stronger cells tend to provide stronger currents, and all cells show a trend to reduce the discharge current rate discrepancy among cells. Future research may focus on working out an algorithm that utilizes this phenomenon to achieve a balanced cell-to-cell condition, and an upper bound on the difference in SOC to connect cells in parallel while avoiding inter-discharging.

### C. CONTROLLER AREA NETWORK (CAN)

Besides keeping a balanced cell states across the pack, another main tasks of the BMS is to ensure information exchange among modules, controllers, and user interface to enable monitoring cells and load state as well as reconfigure switching circuit in real-time. This task can be accomplished with the help of controller area network (CAN) built in the system. CAN [27] is a multi-master serial bus system, which was originally put forward for automotive application in the early 1980's, and internationally standardized by

**TABLE 2.** Command type and command code [6].

| TYPE | NULL | INITIALIZE | BYPASS | PAALLEL | SERIES |
|---|---|---|---|---|---|
| CODE | 000 | 100 | 001 | 101 | 010 |

International Standardization Organization (ISO) as ISO 11898-1 in 1993. The CAN protocol offers a high price to performance ratio and high data transmission speed, thus suitable for real-time applications, such as maritime electronics, factory automation, machine control, non-industrial equipment, and reconfigurable battery pack [33]. Main functions of CAN protocols include:

1. Broadcast communication. Information is transmitted to all devices on the bus. All receivers read the message and decide whether the message is relevant to them.
2. A multi-master hierarchy is set up, which improves building intelligent and redundant.
3. Error detecting protocol and retransmission of faulty message.

### *D. FAULT TOLERANCE*

Fault-tolerant designs are important for obtaining higher system reliabilities, especially for large scale reconfigurable battery systems that are expected to be functional for years. A well-designed fault-tolerant system provides the potential for better availability, permitting the use of circuit elements with a broader range of quality, and lower maintenance cost. To achieve the design goals, the components in the system are supposed to be chosen carefully. The most important parameters in a fault-tolerant system design may include component quality, level of redundancy, redundancy type and implementation, maintenance, etc. The process of handling a fault in a fault-tolerant battery system can be summarized as fault detection, isolation, and correction.

Fault detection, also called fault diagnosis, is the first step towards a fault-free operation. As an important tool for fault detection, accurate software fault diagnosis, which aims at localizing failures in chips, is receiving more and more attention as the size of electronic components goes smaller and physical localization becomes increasingly difficult. Many fault diagnosis tools that are capable of diagnosing various types of faults have been put forward, such as single stuck-at fault (SSF), open fault, bridging fault, etc. [22], [33]. In this work, only SSF is introduced because to our best knowledge, no other fault detection technique is applied in reconfigurable battery pack so far in literature.

SSF model is an abstract, logical, and behavioral model rather than an accurate physical defect model [16]. Abstraction is the main factor of its strength and longevity. By operating in logic domain and staying away from physical details, SSF model remains effective with different design and technologies [34]. For any defect internal to a CMOS simple gate, if it is detectable by some Boolean test, then it is sufficient to test the stuck-at faults on gate terminals. This assertion remains true for complex gates such as XOR, MUX, AOI, etc. Defects external to a gate, for example line open, are detectable by SSF as well. However, SSF vectors detect shorts only by chance. Experiment results have shown that a short is detected with a probability of 75% if SSF test is performed once, which leads to the fact that the probability of short detection rises to over 99% after a SSF vector is repeated 5 times [35]. Since in most tests, each line is tested several times, test escape due to shorts is unlikely and detection probability is close to 100%.

Once a fault is detected, an active fault correction can be conducted since the battery pack topology is reconfigurable and flexible. However, there are still some faults that may not be easy to find out. For example, even though redundancy is added, malfunction of voltage sensors still exists and forms a Byzantine fault, which refers to the situations where multiple observers present different symptoms, and is one of the worst occasions for any system. This type of faults is sure to influence decision making, thus highly likely to result in over-charge, over-discharge. Unfortunately, as far as we know, no current work focuses on investigating the fault tolerance ability in reconfigurable battery pack design, and this issue with faulty sensor is not even mentioned. A typical solution would be adding redundancy, such as two out of three voting strategies to solve this problem with a full understanding of the effect of adding redundancy. Taking Tesla as an example, adding redundancy in a battery pack with more than 6800 single cell introduces a lot of overhead on both hardware and software. Future work may focus on how fault tolerance ability could be improved with minimal cost.

## IV. EXISTING RECONFIGURABLE TOPOLOGY DESIGNS

Developments in multiple disciplines make reconfigurable battery pack feasible to solve the problems introduced by traditional battery packs by increasing battery system flexibility and reconfigurability. In this section, we go through existing reconfigurable battery pack and corresponding designs. A detailed comparison of mentioned frameworks is given in Table 3 at the end of this section.

### *A. EARLIEST DESIGN*

Figure 3 illustrates the proposed design in [2], which provides the flexibility to connect in and remove any single cell from charging/discharging meanwhile allowing arbitrary connection of cells in series, parallel, or hybrid configuration.

To our best knowledge, this is the earliest reconfigurable battery design in the literature that combines single cell

**TABLE 3. Comparison among existing reconfigurable battery pack designs (Y = yes, N = no, NA = not applicable).**

| | Switches per cell | Series Connection | Parallel connection | Hybrid connection | Management complexity | Fault tolerant ability |
|---|---|---|---|---|---|---|
| [2] | 5 | Y | Y | Y | Medium | Strong |
| [17] | 2 | Y | N | N | Low | Low |
| [23] | 2 | Y | N | N | Low | Low |
| [19] | 6 | Y | Y | Y | High | Strong |
| [6] | NA | Y | Y | N | High | Strong |
| [25] | 3 | Y | Y | N | Medium | Medium |

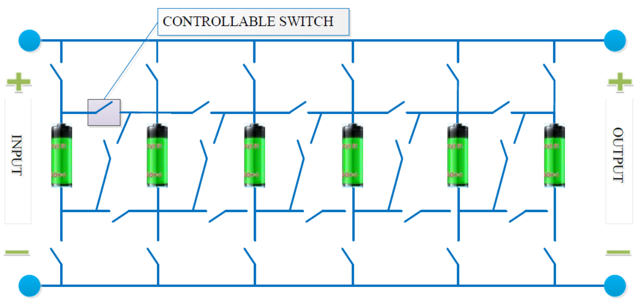


**FIGURE 3. One of the earliest reconfigurable battery pack design.**

behavior with dynamic array level configuration. When n battery cells are connected in series, the current $i_1, i_2, \ldots i_n$ and voltage $v_1, v_2, \ldots v_n$ of those cells satisfy

$$i_1 = i_2 = \cdots = i_n = I \tag{1}$$

$$RC_{series}(i_1, i_2, \cdots, i_n, v_1, v_2, \cdots, v_n) = \sum_{j=1}^{n} RC_j(i_j, v_j) \tag{2}$$

Where $RC_j$ is the remaining capacity of cell $j$. According to the battery model in [17], each $RC_j(i_j, v_j)$ can be expressed as

$$RC_j(i_j, v_j) = \left\{ \frac{1 - \exp(\frac{r_{n,j} \cdot I - (v_{ini} - v_{cuoff})}{\lambda})}{b_{1j}} \right\}^{\frac{1}{b_{2j}}} - \left\{ \frac{1 - \exp(\frac{r_{n,j} \cdot I - (v_{ini} - v_f')}{\lambda})}{b_{1j}} \right\}^{\frac{1}{b_{2j}}} \tag{3}$$

For parallel connected battery cells,

$$v_1 = v_2 = \cdots = v_n = v_{parallel} \tag{4}$$

$$\frac{1}{RC_{series}(i_1, i_2, \cdots, i_n, v_1, v_2, \cdots, v_n)} = \frac{1}{\sum_{j=1}^{n} RC_j(i_j, v_j)} \tag{5}$$

For n*m batteries connected in series-parallel scenarios,

$$RC_{s-p}(i_{11}, i_{12}, \cdots, i_{nm}, v_{11}, v_{12}, \cdots, v_{nm}) = \sum_{i=1}^{n} \sum_{j=1}^{m} RC_{ij}(i_{ij}, v_{ij}) \tag{6}$$

As the earliest framework on reconfigurable battery pack topology design, the major contribution of the work in [2] is that an adaptive reconfigurable multicell structure has been established, and full reconfigurability is achieved, where cells can be connected in a series, parallel, or a mixture of series-parallel fashion. In this way, dynamic operation on cell level becomes possible, which leads to higher efficiency and better reliability.

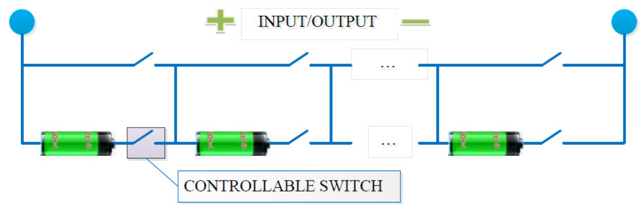


**FIGURE 4. A series-connected reconfigurable battery pack.**

### *B. SERIES TOPOLOGY AND SELF-X*

The work in [18] simplified the previous framework in [2] by proposing a series-connected reconfigurable battery pack as shown in Figure 4, where every two switches are connected with one single cell to control charging, discharging, and cutoff. Compared with the work in [2], the number of switches required per cell is significantly reduced, thus reducing the complexity, cost, and control effort [21]. However, cell level and array level flexibility is compromised. For example, no parallel connection of any arbitrary number of cells is achievable.

The work in [18] has been extended in [23] and [29] by putting forward self-X battery pack design, which stands for self-reconfiguration, self-optimization, self-balancing, and self-healing. The new cell switching circuit is shown in Figure 5, where only one switch is deployed around each cell. As is the case in any reconfigurable battery pack design, cell connections can be dynamically configured during operation according to load demand and the conditions of cells in order to achieve self-healing from cell failures; self-optimizing for maximum capacity delivery efficiency; and self-balancing. Besides, compared to existing reconfigurable battery design [2], [19], [24], the number of switches per cell is significantly reduced.

As shown in Figure 5, the Self-X battery pack employs an m*n cells topology, where m cells are connected in

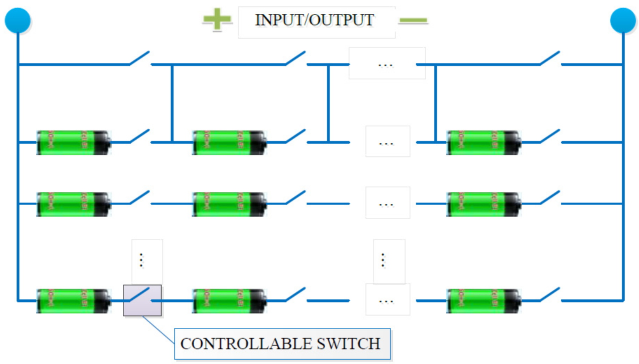


**FIGURE 5.** A Self-X reconfigurable multi-cell battery pack.

parallel to form a bank to provide higher current, and n banks are connected in series to meet higher voltage requirement. One switch is required for each cell to be connected in or cut off the cell from charging/discharging; and additional m switches are used to bypass m banks. Altogether m*(n+1) switches are deployed to form the cell switching circuit and control m*n cells. One prominent advantage of this design is that the number of switches is significantly reduced compared to other reconfigurable multi-cell design. However, the reconfigurability is compromised just like the work in [18]. For example, one cannot connect any two cells from same bank in series. Similarly, cells from same column cannot be connected in parallel, which leads to the fact that not all the capacity is useable.

### C. GENETIC FRAMEWORK

A dynamic reconfiguration framework has been proposed in [19] and illustrated in Figure 6, where six switches are placed around each cell to achieve high reconfigurability. In this design, switches are divided into three categories, namely bypass and series switches by which to bypass or

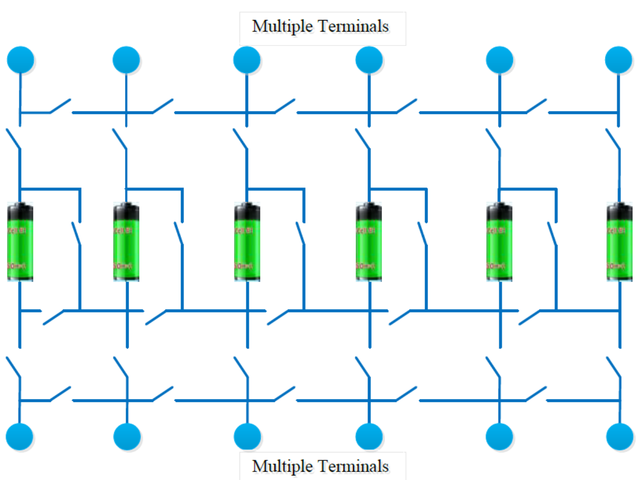


**FIGURE 6.** The topology of the dynamic reconfiguration framework proposed in [19].

connect to the next cell, input and parallel switches by which to connect cells in parallel or series, and input and output terminal switches by which to provide multiple output. Control units monitor voltage and SOC of each cell by measuring and integrating capacity going into or out of battery cell over time, which is known as Coulomb counting method [20].

### D. DESA

Another design named 'dependable, efficient, scalable architecture' (DESA) that supports hierarchical, autonomous management of battery cells was proposed in [6]. As illustrated in Figure 7, DESA employs a typical modular structure that consists of multiple local BMSs and a global BMS. A local BMS is formed by a controller, a set of array-level switches, a CAN module, and sensors; whereas a global BMS is formed by global controller and CAN-based communication module. The global and local BMSs have fully centralized monarchy-based relationships.

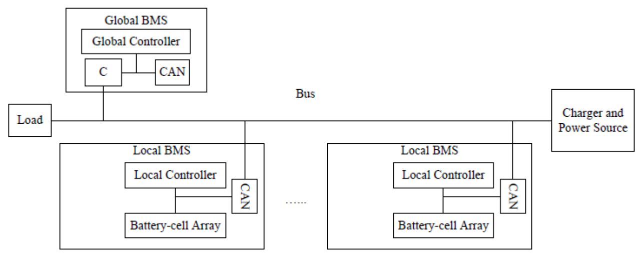


**FIGURE 7.** The schematic diagram of DESA.

Reconfigurability is achieved by adopting a three-switches-per-cell schematic, where B-switch and S-switch are used to bypass a weak cell, and P-switch can make the circuit open. In DESA, 3 digit command code is designed and applied on both the array-level and cell-level to control the state of P-switch, S-switch, B-switch. At the array-level, command codes are issued by global controller according to Table 2, and distributed to individual local controller. The local controllers then execute the command to configure switches. At the cell-level, the commands are executed on individual cells independently.

### E. GRAPH-BASED DESIGN

Much research attention has been paid to investigate how reconfigurability could be achieved and proper management could be conducted. During practical operation of reconfigurable battery pack, there exists another challenge, which is how load requirement can be satisfied by choosing batteries and connecting them into proper topology. Traditionally, voltage regulators are adopted to solve this problem by maintaining output voltage to the required level [26]. However, the energy efficiency may degrade significantly when the difference between required and supplied voltage is large [27], and when the system operates in low power mode [28]. An adaptive algorithm based on reconfigurable battery pack has been proposed in [26] to solve the problem with help of reconfigurability of battery pack. The objective becomes how an optimal system configuration can be achieved based on system reconfigurability, multiple battery states, and real-time load requirement. To solve this problem, the topology of reconfigurable battery pack is abstracted into a directed graph so that the problem of identifying the optimal system configuration is further transformed to a classical path selection in the corresponding graph.

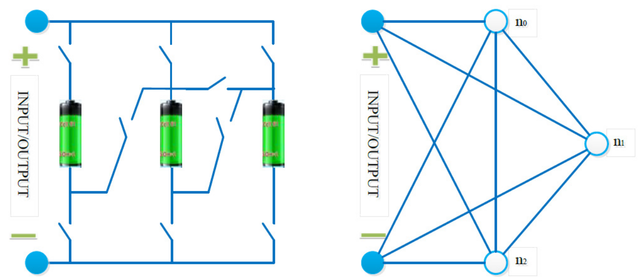


**FIGURE 8. An example of reconfigurable battery pack and the corresponding graph representation.**

An example of reconfigurable battery pack design and corresponding directed graph is shown in Figure 8, where vertex, edge set, and weight of each vertex represent batteries, configuration flexibility, and battery state, respectively. The graph can be further extended to include the terminal pairs if necessary. The problem of finding optimal configuration is transformed to identifying the maximal number of disjoint paths connecting cathode and anode with the summation of weight in the range that could meet load requirement. The approach to solving the problem includes two steps: all feasible paths are identified in the first step, and then the largest disjoint subset will be found in the second step.

Although being inspiring, many deficiencies still exist in this algorithm. As claimed in [25], the proposed algorithm is near-optimal for single load scenario and provides a heuristic solution for multiple load occasions. In addition, even though the directed graph can be extended to include terminal pairs, some circuit properties are still ignored. One counter example would be given as follows: in the directed graph, one possible topology is connecting n0 and n2 in series, and then connects n1 in parallel, which is infeasible in the original battery pack illustrated on the left side of Figure 8.

Considering all topology designs of reconfigurable battery packs shown above, one common problem is that none of the existing designs provide a strong theoretical background on how switching circuit topology is worked out. The significance of this problem is that switching circuit design is foundation of management and algorithm. An optimized and simplified design not only save circuit element, but also ease management, lower computational complexity, as well as consumes less energy. The problem of designing optimized switching circuit can be solved by extending the work in [25], treating anode and cathode of each cell separately as two nodes and investigating connectivity and reachability.

For a given reconfigurable battery pack, the interconnection could be expressed as a directed graph, where the direction is assigned according to the current flow direction during discharging process. It is obvious that no cycle should exist in the graph otherwise the system is at risk of short circuit. In this way the battery pack is abstracted into a directed acyclic graph (DAG) [36], where the reconfigurability of battery pack is closely related to the reachability and connectivity feature of the abstracted graph. For the abstracted directed graph, one is always interested in knowing whether there exists another graph with fewer edges while maintaining the same reachability, which is known as minimum equivalent graph (MEG) problem [37]. Thus, designing a reconfigurable battery pack with high reconfigurability and the minimum number of switches is transferred into identifying the MEG of an abstracted graph, which is also referred to as transitive reduction problem [38], [39] in graph theory.

For a finite DAG, the transitive reduction is unique and identical to MEG. As a result, the designing process is transferred into identifying MEG in a DAG, and can be guided by graph theory. Take the design in [2] as an example, a simplified design with fewer switches while maintaining the same reconfigurability is shown in Figure 9. A reduction in the number of switches will save circuit elements, ease wiring problem, and facility management. Future research may focus on investigating the relationship between reconfigurability and the number of switches deployed around each cell, so that a theoretical upper bound for switch usage can be set to guide industrial design.

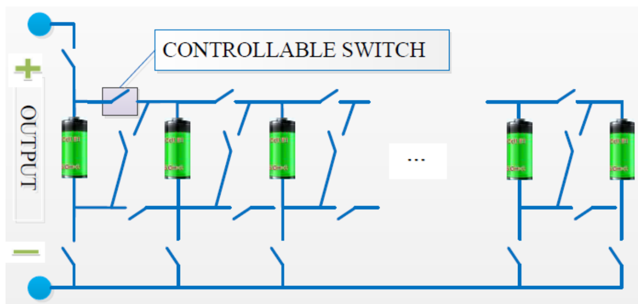


**FIGURE 9. A simplified pack topology with fewer switches while maintaining specified reconfigurability.**

## V. CHARGING IN RECONFIGURABLE BATTERY PACK

As shown in the previous section, much research attention has been paid on reconfigurable battery pack topology design and reconfiguration-assisted discharging. For battery packs, management for charging process is as important as that for discharging. In traditional battery packs, where fixed topology is adopted, it is challenging to get fully charged due to cell-to-cell unbalance issue. As summarized earlier, cell-to-cell unbalance is thought to be the most critical problems, since it always exists and leads to low energy efficiency and safety issue. This issue is particularly serious in traditional battery pack with fixed topology, since the weak

**TABLE 4. Experimental result on delivered capacity with multiple cell balance degree [16].**

| Cell unbalance degree | 0.1 | 0.3 | 0.5 | 0.7 | 0.9 |
|---|---|---|---|---|---|
| Reconfigurable | 2650 mAh | 2650 mAh | 2650 mAh | 2650 mAh | 2650 mAh |
| Non-reconfigurable | 2600 mAh | 2500 mAh | 2450 mAh | 2200 mAh | 2150 mAh |

cells tend to prohibit entire pack from being fully charged or discharged.

Efficient charging of the large-scale is challenging not only because of cell unbalance issue, which terminates charging process when any single cell reaches its voltage upper boundary, but also because of the different charging current required by cells with different voltage. An over-large charging current reduces charging efficiency, and leads to thermal issue and battery aging. On the other hand, a too small charging current prolongs charging cycle unnecessarily, as well as increases internal resistance [14], even prevents the cells from being fully charged [15].

The first attempt to improve charging efficiency in reconfigurable battery pack has been put forward in [16]. The proposed reconfiguration-assisted charging algorithm consists of two steps. In the first step, battery cells are categorized according to their voltage levels, which reflect state of charge (SOC) [66], into groups. Multiple discrete voltage intervals are set and cells are then categorized accordingly. The number of voltage intervals is determined jointly by accuracy requirement and hardware ability. In the second step, the reconfiguration-assisted charging process is carried out in a category-by-category manner with ascending order of voltages. Cells in the first category are charged first in a series connected topology until their voltage reaches second level, which means they become balanced with the second category cells. Then the cells in the second category begin to get charged. This process will be repeated recursively until all single cells in the battery pack are balanced and fully charged.

The topology requirement for charging process is not as strict as that for discharging process due to the fact that charging profile is predefined by designer while discharging profile is determined by real-time conditions and thus unpredictable. The minimum requirement is that the circuit should be able to bypass any single cell in the pack. Figure 10 illustrates a simple example of 3-cell battery pack that satisfies the requirement. This topology is scalable by simply adding batteries and corresponding switches.

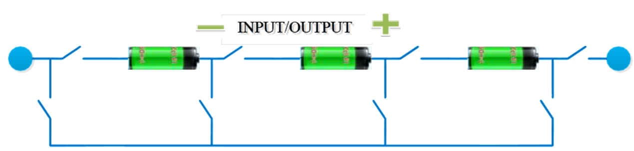


**FIGURE 10. A reconfigurable 3-cell battery pack with the sing-cell bypassing function.**

The overall performance comparisons between traditional charging and the reconfiguration-assisted charging algorithm in [16] are shown in Table 4, where $\Phi$ is a measure of cell unbalance degree, and a larger $\Phi$ indicates larger initial cell unbalance. As can be observed, for non-reconfigurable occasions, the delivered capacity shows decreasing trend as cell unbalance degree increases. On the contrary, with the assistance of system reconfiguration, approximated 2650mAh capacity can be delivered by battery pack stably regardless of cell unbalance degree.

## VI. BATTERY MANAGEMENT SYSTEM IN RECONFIGURABLE BATTERY PACK

BMS is an integrated part in reconfigurable battery pack or system that monitors and manages battery operations. The main functions that BMS performs include monitoring, computation, communication, protection, switching circuit control, and optimization. By performing these key functions, BMS benefits the entire system in terms of safety, accuracy, reliability, scalability, accessibility, and updatability.

From a structure perspective, there have been two types of BMSs, namely flat and modular BMSs [39], [40]. Flat BMS is not practical for application in a large scale, mainly because of the complex wiring problem. Modular BMS, or called modularized battery management systems, are more suitable for a large scale battery system design because of their extensibility in catering hardware of various sizes.

To monitor and control batteries properly, a well-designed BMS should contain features of monitoring, protection, SOC and SOH estimation, cell balancing, and charging control [39]. Functions in a traditional BMS are generalized in [41]. A generic BMS with these basic functions and functions specific for reconfigurable battery pack is illustrated in Fig 11. The bottom level of the BMS involves voltage, current, and temperature sensors that are deployed inside the pack for data acquisition. The data are collected in real-time and are used for thermal management, safety protection, and state estimation. State information is further applied for system level control, such as charging/discharging control, cell balancing, thermal management, and switching circuit control in reconfigurable packs. The functional details of each of the blocks are described in following subsections.

### A. MEASUREMENT MODULES

The measurement block that mainly consists of multiple types of embedded sensors that capture voltages, currents values of battery cells as well as ambient temperature across

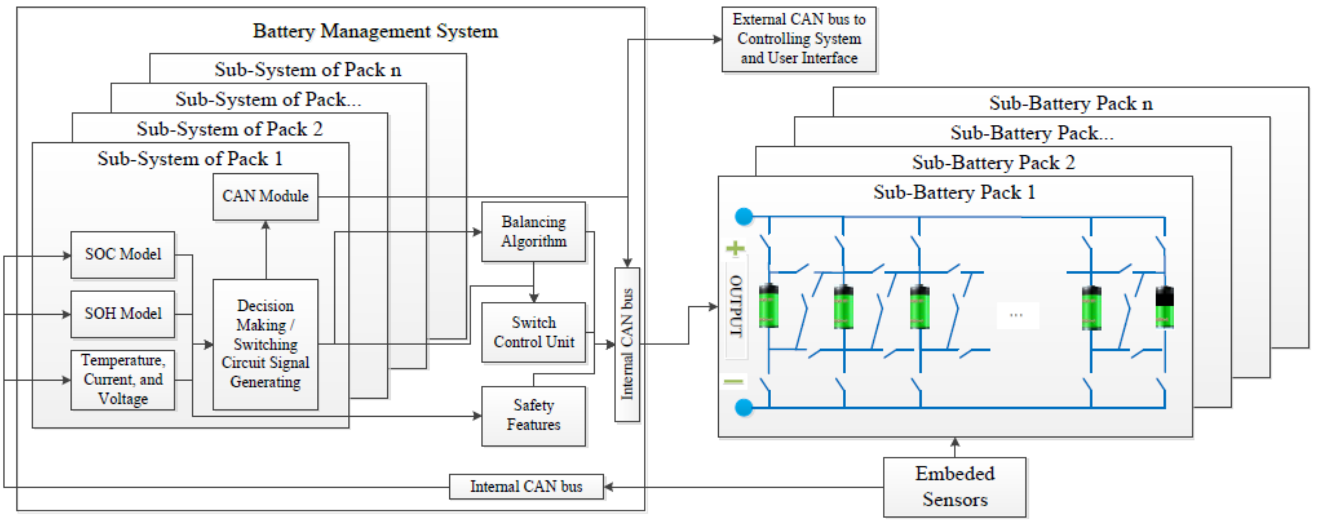


**FIGURE 11.** A typical BMS for a large-scale reconfigurable battery pack.

battery pack [42]. Some research frameworks also adopt extra circuit elements to monitor other battery parameters, such as internal impedance [43]. Accurate measurements from sensors are important, since the measured data is the premise to accomplish any task in the BMS. Requirements on measurement accuracy vary according to application, algorithm, and the type of battery employed. For example, the required voltage measurement accuracy for LiFePO4 battery is extremely high because of the flat OCV-SOC curve in the SOC range of [0.2, 0.8]. If OCV-SOC mapping strategy [45] is adopted, a reliable SOC estimation requires voltage measurement error smaller or equals to 2 mV [60], which is almost impossible in practice. The current sensor is required to be offset free to support Coulomb counting methods as well as other more sophisticated algorithms, where current is fed into dynamic cell models along with measured voltage values.

### B. SOC AND SOH MODULES

Accurate SOC estimation of battery cells with data collected from measurement block is critical for any active operation, such as cell balancing and topology reconfiguration according to load and cell state [58]. Furthermore, SOC is useful to keep battery working in a normal state and avoid the risk of over-charge or over-discharge. Meanwhile, SOC of the entire battery pack is one of the most important outputs of BMS, just like the remaining fuel level in a gasoline car. However, SOC is not accessible through any direct measurement on battery cell. Time-varying environmental conditions and unpredictable discharging profiles make it even more difficult to conduct accurate SOC estimation. The situation is better in reconfigurable battery pack compared with traditional battery pack, since any single battery cell can be disconnected from discharging circuit in a real time fashion. Based on this ability, the research group in GM proposed to estimate SOC by measuring the voltage of a battery cell disconnected from discharging and investigating the hysteresis effect [61], [62]. In this way, OCV is derived, and then the unique OCV-SOC mapping can be performed. However, the accuracy can be questionable for some types of batteries and under time-varying environmental and load conditions. Voltage-based SOC estimation methods are still naive, and much more research efforts are needed in future work.

Another important indicator of battery functionality is state of health (SOH) that indicates the percentage of battery life. SOH is crucial for choosing strategies, algorithms, and guiding substitution of weak battery cells. Compared with SOC, SOH is even more difficult to be measured. Little attention has been paid on SOH, since manufacturers usually only deal with healthy battery cells. So far, there is no consensus on how SOH should be determined. The most frequently used method is comparing the full-charged capacity with the nominal capacity. Other criteria, involving using internal impedance, self-discharge rate, number of charge-discharge cycles, ability to accept a charge, and so forth, has been adopted.

### C. SAFETY FEATURES AND THERMAL MANAGEMENT

One of the key functions of the battery management system is to ensure the safety and prevent battery pack from operating at conditions that may bring about any hazard to user or system itself [44]. Dangerous situations may occur as a result of over-charging, over-discharging, discharging with a current rate that is higher than the safety level, or any operation exceeding safety restriction. Thermal management is an equally important element to ensure safety, especially when a large amount of battery cells are embedded in narrow space. Detailed analysis of safety issue is shown in Section III.

### D. DECISION MAKING, SWITCHING CIRCUIT SIGNAL GENERATING, AND BALANCING

For a given load profile and known SOC values of battery cells in a reconfigurable system, the task of modules to be introduced in this subsection is to configure cell level and array level topology in real time to harness nonlinear effects of battery to achieve higher energy efficiency and ensure safety, while maintaining a balanced cell state across the entire system. One of the major challenges is that a single cell battery itself is a complex nonlinear system with behaviors governed by complex intrinsic chemical reactions, which depend on a variety of operational parameters and environmental factors. Among all nonlinear behaviors, recovery effect and rate-capacity effect are sufficiently significant to influence battery lifetime. Work in [68] presents how recovery effect can be utilized to extend lifetime. Usually, the benefit from harnessing recovery effect contradicts with that from rate-capacity effect, and some time it is challenging to tell which one is stronger. For example, assume there is a small sized reconfigurable battery pack with four identical battery cells in parallel. When load is connected to the pack, there are multiple choices to handle it, including: (1) put all cells in use; (2) put three cells in use at a time; (3) divide cells into two groups that take turn to support the load. A strong rate-capacity effect can be observed in the first scenario, and scenarios 2 and 3 make use of recovery effect. BMS must consider and decide which scenario is the best.

We can provide a theoretical analysis by applying the Kinetic battery model [63] to this scenario. Battery is modeled as two wells in the Kinetic model, where the first well is available charge and the second well is recoverable capacity. A fraction c of the total capacity is put in the first well and a fraction of 1-c in the second well. The charge can flow from second well to the first well through a valve with conductance k. The rate at which the charge flowing between two wells depends on value of k and the height difference between two wells. We may use $c = 0.40168$, $k = 0.5821$, $k' = 0.1399$, $d = 3.2$Ah, and load equals to 3A. The final calculated lifetime values for these three scenarios are 15342s, 15348s, and 15338s, respectively. Three scenarios show quite similar lifetime value, and in this case, the first scenario is the best choice, since it is easy to implement, and less switch operation and smaller current value in each cell are good for battery health as well as circuit element lifetime.

However, sharing load among all cells is not always the optimized choice under various scenarios. When the scale of the system grows larger together with the cell-to-cell variance and the unbalance issue, the problem becomes extremely complicated. Unfortunately, no existing research work really focuses on it and goes into details. Much more time and efforts are needed for sophisticated BMS designs.

## VII. APPLICATIONS, LATEST STATUS, AND OUTCOMES

A large body of research has investigated techniques related to reconfigurable battery packs that have been gaining popularity in industrial applications such as EVs, data centers, smart grids, as well as other cutting-edge battery systems, such as software defined batteries (SDB) [55] jointly proposed by Microsoft Corporation, Tesla Motors, University of Massachusetts Amherst, and Columbia University. The basic idea of SDB is to satisfy load demand by discharging multiple types of cells with different battery chemistries. A growing range of battery chemistries are under development, and some of them outperform the others on one or a few aspects, such as peak power, longevity, energy density, and efficiency. Combining multiple of heterogeneous batteries enables SDB to trade among multiple types of battery capabilities dynamically, thereby achieving the optimal performance.

**FIGURE 12. (a) Reconfigurable battery pack in UPS replacement in data centers; (b) The first large-scale reconfigurable battery system with 1792 LiFPO4 26650 battery cells.**

However, traditional battery pack designs of deploying battery cells in fixed topologies are apparently not suitable for SDB operations, since no cell level or array level flexibility is introduced. In SDB, on the other hand, the fine-grained control of the amount of energy is enabled by adopting a smart switching circuit. The work on SDB opens up battery chemistry as one parameter for system and algorithm designer, which is previously unavailable, and also starts a new research area of reconfigurable battery.

Another typical electrical system that adopts a large amount of battery cells is smart grids. In traditional power grid, the peak load demand is met by increasing the consumption of fossil fuels, which always leads to low efficiency and unsustainable issues [46]. The centralized power system in modern industry is about to transfer into a customized and distributed power generation and utilization system, and the optimization can be done by energy sharing and reallocating, just as information in the Internet.

Currently, researchers in this field mainly focus on exploring the potential core technologies of the energy Internet [54]. Prior work has analyzed energy internet models based on energy exchange technologies, such as energy router [47], [48]; requirements on the information collection and on the microelectronic technology from energy storage and communication equipment [49]; information collection system architecture and method based on energy consumption and energy gateways [50]. In recent work, the distributed energy storage system is recognized as one of the most important foundations for energy internet development [51]. Energy storage is the core technology to match power generation and consumption, which has the functions of stabilizing fluctuations, matching supply and demand, and improving power supply quality, and thus becoming essential equipment in renewable energy generation systems. A variety of methods and storage carriers for energy storage systems have been utilized, including batteries, flywheels, pumped water, super capacitors, and compressed air. Among all these, battery storage systems have incomparable advantages on energy storage levels from kilowatts to megawatts [52], [53], [67]. According to the report from DOE, lithium batteries outperformed any other batteries in terms of energy efficiency, energy density, and scalability, so that battery packs consist of lithium battery are recognized as one of the most promising energy storage carriers for EVs, smart grids [54].

Besides being used as the energy storage system in power grid and the power system in EVs, reconfigurable battery is also applied as backup power in data centers as shown in Figure 12. One primary consideration for the construction of a data center is the energy supplying capacity of the location, since the issues of energy consumption and carbon emission are becoming increasingly serious. According to statistics, by the end of 2012, the number of data center all over the world has reached 3.6 million; the number of server units has reached 3.4 million with the increasing rate of 14% every year. Rapid data center deployment in number intensifies the energy consumption issue. From 2011 to 2012, the energy consumption of all data centers grows from 210 billion kWh to 332 billion kWh, which is a 63% increase, and also resulted in significant increase in carbon emissions. According to an assessment from Natural Resources Defense Council, up to 50% of energy in data center and smaller server rooms is wasted due to lack of awareness and incentives to make them more efficient [70].

Recently, research attention has already been paid on this area. The first Energy-Internet-based distributed energy storage system has been developed and applied in data centers. This system is the known as the largest reconfigurable battery network with 1792 lithium battery cells, in which each cell is monitored and controlled independently in a real time fashion. A switching circuit enables reconfiguration on cell level topology within 10 milliseconds. As a result, management in this system can be conducted dynamically on cell level, array level, pack level, and battery network level by means of network and information. Higher energy efficiency, better safety and reliability can be achieved through proper management on cells and reconfiguration on cell topologies. Meanwhile, the system is capable of isolating arbitrary faulty cells as well as achieving cell-to-cell balanced condition. Study in [60] indicates that the lifespan of the prototype is almost twice as long as that of traditional battery pack with fixed topology and the same amount of single cells under the identical load and operational conditions. Furthermore, the distributed energy storage system also paves the way for high utilization of repurposed battery cells.

## VIII. CONCLUSION

In this paper, we presented a comprehensive survey on reconfigurable battery pack design. Design challenges and hazarders are presented as well as existing key techniques, applications, latest status, and outcomes. We also listed the designs that have already been proposed in literatures. In addition, we investigated design problems with the help of graph theory and simplified an existing design. Possible future research directions in different areas have been discussed.

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