Design Automation for Battery Systems

(*Invited paper*)

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ABSTRACT

High power Lithium-Ion (Li-Ion) battery packs used in stationary Electrical Energy Storage (EES) systems and Electric Vehicle (EV) applications require a sophisticated Battery Management System (BMS) in order to maintain safe operation and improve their performance. With the increasing complexity of these battery packs and their demand for shorter time-to-market, decentralized approaches for battery management, providing a high degree of modularity, scalability and improved control performance are typically preferred. However, manual design approaches for these complex distributed systems are time consuming and are error-prone resulting in a reduced energy efficiency of the overall system. Here, special design automation techniques considering all abstraction-levels of the battery system are required to obtain highly optimized battery packs. This paper presents from a design automation perspective the recent advances in the domain of battery systems that are a combination of the electrochemical cells and their associated management modules. Specifically, we classify the battery systems into three abstraction levels, cell-level (battery cells and their interconnection schemes), module-level (sensing and charge balancing circuits) and pack-level (computation and control algorithms). We provide an overview of challenges that exist in each abstraction layer and give an outlook towards future design automation techniques that are required to overcome these limitations.

CCS CONCEPTS

• **Computer systems organization → Embedded and cyber-physical systems**; *Distributed architectures*; • **Hardware → Batteries**;

KEYWORDS

Batteries, battery management systems, design automation

ACM Reference Format:
Swaminathan Narayanaswamy, Sangyoung Park, Sebastian Steinhorst, Samarjit Chakraborty. 2018. Design Automation for Battery Systems: (*Invited paper*). In *IEEE/ACM INTERNATIONAL CONFERENCE ON COMPUTER-AIDED DESIGN (ICCAD '18), November 5–8, 2018, San Diego, CA, USA.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3240765.3243469

ICCAD '18, November 5–8, 2018, San Diego, CA, USA

ACM ISBN 978-1-4503-5950-4/18/11...$15.00
https://doi.org/10.1145/3240765.3243469

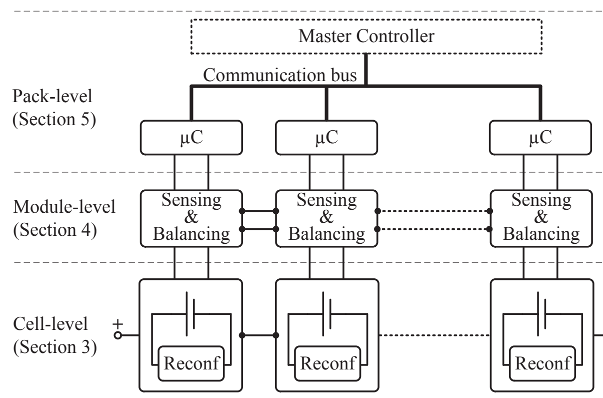

Figure 1: Battery Systems combining the electrical interconnection of battery cells at cell-level, the sensing and balancing at module-level and the controllers at the pack-level.

1 INTRODUCTION

Lithium-Ion (Li-Ion) batteries, with their high energy and power densities, are a preferred option of implementation for high power applications such as Electric Vehicles (EVs), Hybrid Electric Vehicles (HEVs) and stationary Electrical Energy Storage (EES) systems. Large battery packs for these high power applications typically comprise individual Li-Ion cells interconnected in parallel/series forms, where a parallel-connection increases the capacity and the series-connection of these parallel cell modules achieves higher voltages. In spite of their high energy and power densities, Li-Ion cells are highly sensitive to their operating conditions [1]. Any out-of-specification operation in terms of voltage, current or temperature will severely damage the cells reducing their lifetime and also cause fire or explosion due to thermal runaway. Moreover, manufacturing differences and varying temperature distribution along the battery pack lead to variations in the State-of-Charge (SoC) of individual cells in the pack. As a result, the usable capacity of the battery pack is reduced since a series-connected pack can only be discharged or charged till any cell in the pack reaches its lower or upper SoC threshold, respectively.

Battery Management Systems (BMSs): To maintain the operating conditions of the Li-Ion cells within their allowed limit, a sophisticated Battery Management System (BMS) is required. The BMS monitors the parameters such as voltage, current and temperature of the cells and controls the battery pack such that no cell in the pack crosses the safe threshold limits. In addition, the BMS also controls the balancing circuitry which equalizes the charge

This work was financially supported by the Bundesministerium für Bildung und Forschung, award number: 01DQ17018 (FuturTrans). With the support of the Technische Universität München - Institute for Advanced Study, funded by the German Excellence Initiative and the European Union Seventh Framework Programme under grant agreement no: 291763.

variations among the cells in the pack. Conventional techniques for balancing rely on passive approaches, where the excess charge in the cells is dissipated as heat across a resistor. In contrast to this, energy-efficient active cell balancing methods are gaining more importance where the SoC variation among cells is minimized by redistributing the excess charge among the cells. As such the BMS falls under the domain of Cyber-Physical Systems (CPSs) where the physical processes such as voltage, temperature and current of each cell and the control algorithms that maintain these physical parameters within the safe limits, thereby forming the cyber part, are modeled and designed in a tightly integrated fashion.

Design Automation: Due to the growing complexity of battery packs and the increasing demand for shorter time to market of applications that use these battery packs, the BMS design is moving towards a decentralized architecture in order to achieve a high degree of modularity, scalability and improved control performance with minimal integration efforts. Here each cell in the series string of the battery pack is associated with an intelligent control unit that monitors and maintains the parameters of the cells within their safe limits and also coordinates with other cell-level control units to perform the system-level management functions. However, manual design approaches followed for conventional BMS architectures might not be efficient for these decentralized topologies leading to erroneous system design. For instance, the more recent active cell balancing circuits [15, 25] consist of modular electrical architecture that can be attached to each cell and enable complex charge transfer capabilities such as direct charge transfers between non-adjacent cells in the pack. Consequently, these balancing architectures have a high number of circuit components interconnected in a non-trivial fashion and require a complex control scheme with multiple high frequency Pulse Width Modulated (PWM) signals having tight timing constraints. Ensuring correct functionality of these balancing architectures is essential to prevent configurations that will lead to hazardous conditions such as short circuits between the cells. Manual design and verification of such complex balancing architectures is tedious, error-prone and in certain cases might be infeasible due to the high number of possible scenarios that have to be evaluated, thereby preventing rapid development of new active cell balancing architectures. Here an automated approach for designing and verifying the correct functionality of complex balancing architectures using a set of design rules will significantly improve the efficiency of the battery pack and also shorten the time-to-market of the application that uses these high power battery packs. Similar requirements for design automation techniques can be observed at all abstraction-levels of battery systems as will be explained in the remainder of the paper.

Organization: While several design automation tools are available for efficient design of integrated circuits, they cannot be directly applied for battery systems that fall under the domain of CPSs. Therefore, special design automation tools and techniques focusing on all abstraction-levels of the battery packs are required to be developed to obtain highly optimized systems with minimal cost and shorter time-to-market. Towards this, in this paper, we introduce the concept of *battery systems* that include the underlying electrochemical Li-Ion cells, their electrical interconnection scheme to form a battery pack and their associated management algorithms. Particularly, we classify a battery system into three abstraction levels namely, the cell-level, module-level and the pack-level as shown in Figure. 1. The cell-level (Section 3) comprises the Li-Ion cells and their different interconnection schemes, module-level (Section 4) focuses on the sensing and balancing aspects and the pack-level (Section 5) explains the system-level management algorithms. In the following sections, we explain the challenges associated with each abstraction-level of the battery systems and provide an outlook towards future design automation tools that are required to overcome these challenges.

2 TRENDS IN BMS TOPOLOGY

The topology of a BMS is defined as the electrical and logical arrangement of modules that perform sensing of cell parameters such as voltage and temperature, computation of cell states such as SoC and State-of-Health (SoH) and control of balancing circuits. In this section, we provide an overview on the recent advancements in the BMS topology that enable us to understand the system requirements and develop appropriate design automation techniques and tools targeting the critical parts of the system.

2.1 Conventional BMS Topologies

Figure 2 shows the trend of the BMS topologies in the literature. Conventional approaches are either centralized or hierarchical as shown in Figure 2a and 2b, respectively.

Centralized (Figure 2a) and Hierarchical (Figure 2b): In the centralized approach each cell is associated with a Sensing and Balancing Module (SBM) as shown in Fig. 2a, measuring the voltage and temperature of each cell [2]. A single Current Sensor (CS) can be used to measure the pack current since the current flowing through all the cells will be equal as they are connected in series. The balancing part of the SBM will typically be a simple high power resistor in series with a power transistor realizing a passive balancing approach. The individual SBMs are controlled by a single master controller, which in addition to maintaining safe operation of each cell, also implements the pack-level functions such as pack SoC and SoH calculations. Alternatively, the hierarchical approach introduces an intermediate control layer in the form of Module Management Units (MMUs) as shown in Fig. 2b, managing the properties of a certain group of cells, relieving the Pack Management Unit (PMU) for performing only pack-level functions [3].

Challenges: *Scalability* of these conventional approaches is significantly limited. The design of the electrical architecture of the SBM and the MMU is highly integrated with the underlying cell and its parameter specifications. Similar dependence is also observed in the management algorithms of the master controller in both centralized and hierarchical approaches, which have to be modified depending upon the application scenario. Moreover, addition of new cells to the pack will not be easily supported and requires a complete redesign since the computational capability and the input/output performance of the master and the MMUs are limited that do not scale with the amount of cells. In addition, the *balancing* capability of these approaches is often limited to energy-inefficient passive techniques since the more energy-efficient active balancing approaches require a complex control scheme that cannot be satisfied by a single master controller while performing other critical pack-level BMS functions. Therefore, there exists a trade-off

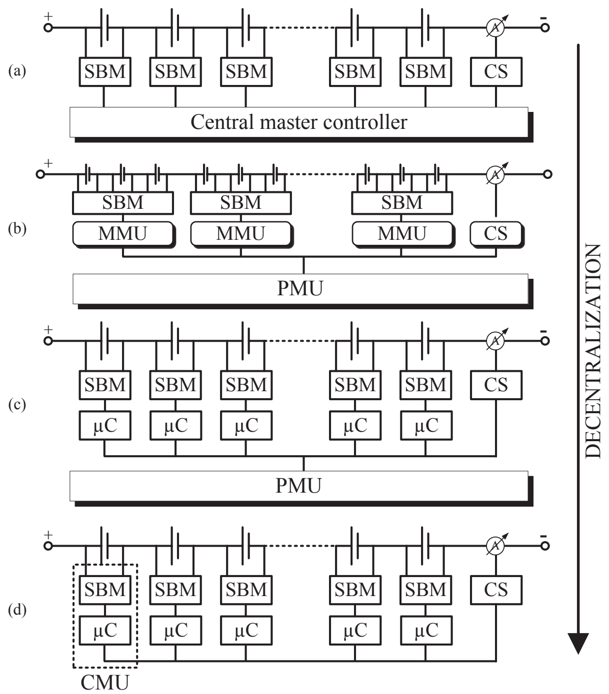

Figure 2: Trends in BMS topologies. (a) Centralized, (b) Hierarchical, (c) Partially distributed and (d) Fully decentralized (smart cells).

in designing the master controller for these topologies to avoid an expensive over-designed controller or an unsafe under-performing control unit.

2.2 Emerging Decentralized BMSs

With increasing applications of battery packs and the demand for shorter time-to-market, the system integration aspects of battery systems are gaining more attention. Here methods for customization-free plug-and-play integration providing a high degree of scalability and reliability are of paramount importance. For this purpose, the system architecture must consist of homogeneous modules with high computational and controlling capability enabling automated design and verification. This trend resulted in distributing the control and computational units close to each cell adding more intelligence at the cell-level.

Partially (Figure 2c) and fully (Figure 2d) decentralized: First approaches for decentralization were proposed in [4] as shown in Figure 2c, where each cell is monitored with a dedicated cell-level control unit that is in turn connected to a light-weight master controller. Here, the local controllers perform the cell-level functions of the BMS such as cell voltage, temperature measurements, SoC and SoH calculations and control of the individual balancing units, while the light-weight master only performs system-level BMS functions. By contrast, [5] proposes a fully decentralized system topology as shown in Figure 2d, where the local cell-level controllers together with the SBM form an autonomous Cell Management Unit (CMU), thereby managing all the parameters of the cell it is attached to. The cell along with this CMU is termed as the *smart cell*, and the battery pack is formed by interconnection of these individual smart cells that perform all the pack-level functions such as cell balancing or pack SoC calculation in a cooperative fashion adopting techniques from the domain of self-organizing distributed systems.

Benefits of decentralization: Having homogeneous electrical circuit architecture and algorithms for the cell-level controller favors mass production and customization-free integration and thereby significantly increases the scalability of the system. Furthermore, adding more intelligence to each cell enables accurate monitoring and control of cell parameters within their allowable limit and timely reaction to faults in the system. Moreover, the decentralized approaches do not suffer from single point of failures commonly experienced in the conventional architectures. Failure of a single cell-level controller will only render the associated cell unusable and failure of the master controller in case of partially distributed topology will not be catastrophic since the individual cell-level controllers can still function without the supervision of the master. Finally, increasing the computational and controlling capability at the cell-level promotes the realization of complex active cell balancing architectures and reconfigurable approaches significantly improving the overall usable capacity of the battery pack.

In summary, the battery management and system design is moving towards a decentralized architecture in order to improve the monitoring and controlling capabilities. However, there exist several challenges in achieving this trend, which reflect on all abstraction-levels (cell-level, module-level and pack-level) as will be explained in the following sections.

3 CELL-LEVEL

Cell-level involves the battery cells and their multiple possible interconnection schemes to form a high power battery pack. Just as design automation for semiconductor devices should consider various factors such as the critical path delay, chip area, power consumption, heat dissipation, cost and reliability, *design automation* for battery systems at cell-level also has several design requirements/criteria. The most basic requirements are the power and energy capacity of the battery system, which can be fulfilled by interconnecting multiple cells to form a pack. On the other hand, constraints such as energy and power densities, usable capacity, longevity, safety, reliability, cost, etc, apply depending upon the application. These factors are affected by the cell-level interconnection schemes as we will see in the subsequent sections.

3.1 Static and Reconfigurable interconnection schemes

The most basic method to fulfill the energy and power capacity requirements of a battery-powered application is to use multiple cells and connect them in series and/or parallel. Most conventional battery packs adopt a static interconnection scheme where the connection pattern of multiple cells is fixed throughout the battery lifetime. Recently, reconfigurable topologies that dynamically modify the cell interconnection schemes are gaining importance due to several advantages as will be explained in this section.

Static interconnection scheme: The most popular static interconnection scheme is *series-of-parallel* connection [6]. Cells are first connected in parallel to increase the current capacity as shown in Figure 3a. Then, parallel modules are connected in series to increase the pack voltage. An alternative interconnection scheme is *parallel-of-series* connection. Cells are first connected in series to form a

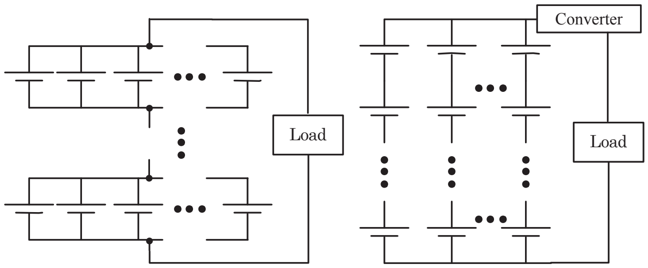

Figure 3: (a) series-of-parallel, (b) parallel-of-series interconnection schemes.

string, and then connected in parallel to increase the current capacity as shown in Figure 3b. While both architectures are identical if there is no cell-to-cell variations, however, in reality there exist several differences among the individual cells due to manufacturing inhomogeneities and also uneven operating conditions. As a result, it is important to analyze the advantages and disadvantages of the individual connection schemes to identify the best approach for a particular application.

The series-of-parallel scheme benefits from the fact that the variation among cells that are connected in parallel is naturally balanced as they must have the same terminal voltage and can be considered as a single cell with high capacity. As a result, the balancing approaches for this type of interconnection scheme also become relatively simple since they must only focus on equalizing the charge level of cells that are connected in series. However, the scalability of the pack is compromised as addition of cells to the existing pack in order to increase its capacity is not possible. On the other hand, the parallel-of-series connection scheme allows seamless addition of new strings to the pack for achieving higher capacity. Nevertheless, the cell-to-cell variations will result in high inter-string currents that will eventually reduce the usable capacity and lifetime of the pack.

Reconfigurable interconnection scheme: While most real-world battery systems adopt static interconnection schemes, the potential of dynamically reconfigurable interconnection schemes has also been investigated recently by the research community [7–9]. One such example of reconfigurable interconnection scheme is shown in Figure 4 [9]. Here, three switches per cell are used to dynamically change between series or parallel interconnections or to isolate the cell from the pack. If the bypass switch, S_1, is closed, the cell will be isolated from the rest of the pack. Series connection switch S_2, connects the cell and the one on the right in series. Parallel connection switch, S_3, connects the adjacent cells in parallel.

Proper design and usage of such schemes could enhance several performance metrics of the pack. For example, dynamic reconfiguration could increase the usable energy of a battery pack during discharging by balancing the charge among cells. If a cell in a pack is particularly weak having smaller energy than rest of the cells, reconfiguration could restrict the usage of the cell by bypassing it or connecting it in parallel with stronger cells [10]. Moreover, such reconfiguration approaches also increase the reliability of the pack by bypassing faulty cells that have output voltage as low as the cut-off voltage or have capacity smaller than 80% of nominal capacity. Dynamic reconfiguration could also be beneficial during charging,

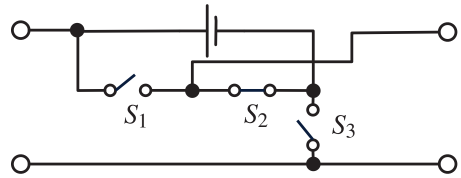

Figure 4: An example reconfigurable interconnection scheme with three switches per cell [9].

especially *fast charging*. If a single Li-Ion cell is particularly charging faster compared to other cells, the cell could be simply bypassed until the other cells are fully charged. Furthermore, reconfiguration could be utilized to enhance the energy efficiency during charging by increasing the number of cells in series by reconfiguration in order to reduce the ohmic loss [11].

3.2 Challenges and Future Design Automation Methods for Interconnection of cells

Challenges for Parallel-of-Series packs: While the series-of-parallel interconnection scheme has been extensively studied in the past, less study has been performed in the literature regarding the parallel-of-series connection approach. The primary challenge of this interconnection scheme is to counteract the imbalances between the individual strings forming the pack. Depending upon the cell placement in the pack and the efficiency of the cooling system to maintain homogeneous operating temperature, variations in capacities among cells in the individual strings tend to increase. In such cases, different terminal voltages among strings occur, leading to large inter-string currents that increase the power dissipation and also results in faster aging of the individual cells. One recent study in [12] pointed out that proper characterization of cells and appropriate placement during pack manufacturing for the parallel-of-series interconnection scheme could have higher benefits compared to series-of-parallel approach. Moreover, the parallel-of-series interconnection scheme is typically used for the purpose of extending the pack capacity at a later stage. However, the newly added string of cells will have a different aging and discharge characteristics than the remaining strings further increasing the imbalances in the pack. Therefore, novel cell balancing approaches are required here to minimize these variations by selectively discharging or charging the cells in the individual strings based on their remaining SoC, SoH and resistance.

Challenges for reconfiguration: One of the main challenge for reconfiguration approaches is the power dissipation across the switches [9]. For instance, a Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) switch having 5 mΩ for an 100 A pack current will have 50 W of power dissipation per switch in the current path, which is an unacceptably large value for many applications such as EVs or stationary EES systems. Moreover, with frequent switching, the terminal voltage of the battery pack changes drastically that might not be suitable for certain applications such as EVs where the battery pack is directly connected to the inverters without any intermediate DC-DC converters. Therefore, reconfiguration approaches must be designed to achieve a higher energy efficiency considering the losses involved with an additional DC-DC converter stage [13]. Furthermore, existing reconfiguration approaches are typically proposed for centralized or hierarchical BMS topologies, where a single master controller makes all the decisions regarding the control scheme of the reconfiguration switches. However, integrating them with the recent decentralized approaches introduces a special set of challenges [14], since the individual cell-level controllers do not have the global system knowledge. This requires extensive communication between the cell-level controllers for identifying the optimal control scheme for their associated reconfiguration modules and at the same time ensuring battery pack-level optimality.

Future design automation techniques: Assessing the effectiveness of a reconfiguration scheme requires detailed models of the comprising components, and evaluation of various metrics such as energy efficiency, longevity, system complexity, cost, and so on. Moreover, automated synthesis of the switching scheme for these reconfiguration approaches depending upon the load, operating conditions such as temperature of the pack, aging of cells, efficiency etc, will significantly improve its design process. Such automated synthesis approaches must also be designed for implementation towards decentralized BMS topologies considering their specific constraints in terms of control and communication capabilities. Furthermore, the design automation approaches for such reconfigurable techniques must also be capable of performing automated functional verification of the control scheme, especially in case of decentralized BMS topologies. This requires special set of design automation tools to be developed involving modeling and simulation at various abstraction-levels of the battery system.

4 MODULE-LEVEL

The sensing and the balancing parts form the module-level abstraction of the battery systems as shown in Figure 1.

4.1 Sensing Module

Accurate sensing of cell parameters such as its voltage and temperature is vital part of the battery system design as it impacts the accuracy with which the system-level properties such as pack SoC and SoH are calculated. Measurement of individual cell voltages, especially in a series-connected battery pack with decentralized BMS topologies as explained in Section 2.2, is an extremely challenging task since the DC potential of each cell varies along the series chain. For instance, the voltage across the terminals of cell that forms the negative terminal of the pack will vary from 0 V to 4 V, whereas for the cell at the positive battery pack terminal the voltages will be from 396 V to 400 V for a pack consisting of 100 cells in series. Since the sensing module is powered from the battery cell itself, the varying ground potential introduces a huge common-mode noise that has to be taken into consideration. Moreover, the voltage profile of the Li-Ion cell is extremely flat during continuous charging or discharging and on the other hand exhibits second-order non-linearity with varying time constants during a transient response. Therefore, the sensing module must have a large bandwidth with high accuracy and resolution in order to precisely measure the cell voltage during different discharge phases.

While several electronic design automation techniques exist for designing amplifiers to minimize the effects of Common Mode Rejection Ratio (CMRR) (common-mode noise) and Power Supply Rejection Ratio (PSRR) (power supply noise), the design of cell voltage measurement amplifiers is different and these techniques cannot be directly applied here. This requires development of accurate battery cell models that capture the cell transient and steady-state behaviors for different discharging and charging patterns. In addition to the individual cell models, the battery system response, which contains the individual cells in series and/or parallel connections, has to be modeled for designing the sensing module.

4.2 Balancing Module

With the increasing trend towards decentralization of BMSs, implementation of complex active cell balancing circuits are gaining more importance. These active balancing systems are a combination of power electronic modules consisting of inductors, capacitors or transformers and power MOSFETs controlled by an embedded platform in the form of a microcontroller generating the necessary actuation signals. While decentralization addresses the control requirements of the balancing module, the focus now shifts towards the electrical architecture design and its verification in order to satisfy the modularity and homogeneity requirements of the decentralized BMS topologies.

Electrical architecture design: The modularity of the decentralized BMS topology imposes strict constraints on the electrical architecture design of the active cell balancing unit as detailed in [15]. Balancing modules must contain homogeneous electrical architecture that could be attached to each cell of the pack. Moreover, all high frequency control signals required for performing charge transfers between cells must be generated locally by the cell-level controller (CMU) without requiring any synchronization with other controllers in the pack. In addition, [15] points out that the balancing architecture should (i) enable direct charge transfers between non-adjacent cells in the pack, (ii) achieve high number of simultaneous charge transfers, (iii) have a reduced number of switches and (iv) require a low number of high frequency control signals, in order to achieve high energy efficiency.

Optimal component selection: Optimal selection of circuit components is a crucial design step for active cell balancing architectures, since each charge transfer activity involves a certain energy dissipation due to the parasitic resistances and capacitances of the circuit components in the system. Intuitively, a designer will select the circuit components that have the least parasitic resistances and capacitances to build the balancing architecture. However, this will not be energy-efficient and optimal from a system-level perspective, since there exist a trade-off between the different types of losses introduced by these parasitic circuit components. This trade-off is further aggravated by the controlling frequency of the balancing architecture, which has to be appropriately selected to satisfy the timing requirements. Here a detailed analytical model of the balancing architecture taking a holistic perspective capturing the impact of all the individual parasitics in the circuit components and their relations is required.

Verification of balancing architectures: There have been several such active cell balancing architectures [15–18] proposed in the literature with varying functionalities requiring a complicated control scheme. Verification of the correct functionality of these architectures is an essential task to avoid hazardous conditions such as short-circuits between the cells. However, performing a manual verification is infeasible due to the high amount of possible scenarios and becomes a non-trivial task leading to error-prone results. Moreover, tools typically used for circuit functionality checks such as SPICE are highly inefficient due to the large number of switches and specific complex control schemes required for these architectures. Here, an automated verification tool that considers the circuit architecture and the control scheme concurrently is required to enable rapid development of complex and energy-efficient active cell balancing architecture.

Existing design automation tools: Several design automation techniques have been proposed in the literature to address the above-mentioned challenges in the design of active cell balancing architectures. For instance, [19] proposes an automated architecture synthesis framework, that combines a satisfiability solver to explore the search space for identifying an optimal active cell balancing architecture satisfying the design rules in [15]. On the other hand, optimal dimensioning framework proposed in [20] identifies energy-efficient combinations of the circuit components (inductors and MOSFETs) from a set of commercially available off-the-shelf components that results in high efficiency. Similarly, the approach in [21] optimally sizes the energy storage element (inductor) of an active cell balancing architecture that will achieve higher performance than off-the-shelf components. In addition to tools for designing the electrical architecture of active cell balancing circuits, automated verification approaches have also been proposed in the literature. [16] uses a graph-based approach to functionally verify the switching schemes of any complex active cell balancing architectures. Similarly, [22] extends this graph-based model by adding formal verification techniques to prove the system properties and are extended to enable synthesis of optimized and correct-by-construction active cell balancing circuit architectures.

Future design automation techniques: Multiple improvements are possible for the existing design automation techniques to increase the efficiency of the balancing architecture and minimize their design time. For instance, the automated synthesis framework in [19] can be integrated with the optimal dimensioning tools proposed in [20] and [21] thereby developing an *optimal synthesis framework* that allows to automatically design the circuit architecture and optimally dimension the components of an active cell balancing architecture for achieving high energy efficiency. Furthermore, the verification approaches in [16] and [22] could also be integrated with this *optimal synthesis framework* such that the optimally synthesized balancing architectures are automatically formally verified for their functionality. As such, the individual tools can be integrated to form a comprehensive design automation framework that performs automated design, optimization and verification of future active cell balancing architectures.

5 PACK-LEVEL

On the pack level, battery systems design addresses the aspects of optimally utilizing the architecture components provided on the cell and module levels, such that the efficiency, energy output, charging capability and lifetime of the battery system are maximized.

From a design automation perspective, this comprises two major aspects which will be discussed in this section. First, we will introduce a design methodology for active cell balancing strategies, as these are strongly impacting the effectiveness and efficiency of battery packs. The second aspect will focus on emerging frameworks to automate the design process for battery system architectures, enabled by advanced simulation and analysis tools.

5.1 Design Methodology for Cell Balancing Strategies

While the active cell balancing circuit architectures presented in the previous section provide the capabilities to perform the actual charge transfer between cells, advanced strategies how to operate the circuitry can be developed using design automation methods. A balancing strategy defines how to operate the circuit architecture regarding the pairing and order of charge transfers. The pairing determines which cells act as the source for charge transfers and which cells act as the destination. For such pairings, a temporal order of charge transfers and their amount of concurrency depending on the capabilities of the hardware architecture are then computed.

The main goal of active cell balancing is to equalize the SoC across all series-connected cells in the pack in order to maximize the effective capacity of the battery. Here, the transfer efficiency is the metric to determine the quality of the balancing strategy and the underlying hardware. In [23], four optimality criteria for the balancing process have been developed, with the most important one determining how an efficient strategy has to perform in order to minimize charge losses during the balancing. While active cell balancing transfers charge between cells, the process is not completely lossless. The resistance of the components in the current path creates a small power dissipation. When charge is transferred between neighboring cells in one direction, a later transfer should not require charge flow in the opposite direction, as this would render the initial transfer inefficient. Consequently, the SoC change of each cell should be monotonic except the case that a cell is used as a shuttle cell where it receives charge from a neighbor to hand it over to the other neighbor. Furthermore, the global direction of charge transfers should always be monotonic, hence working towards the global equalization goal. The remaining optimality criteria discuss how to minimize balancing time until an equilibrium is reached, to maximize the usable pack-SoC as early as possible during balancing and to minimize the stress on cells induced by balancing. At the same time, secondary goals can be mapped to a corresponding strategy, such as considering the SoH of cells for mitigation of battery aging [24].

Most charge equalization strategies consider a central control perspective where a master controller takes decisions on the steps of the balancing process [17, 18, 25]. Recently however, with the introduction of decentralized BMS topologies, a new class of strategies for smart battery cells has been developed, where no central entity makes decisions but all cells collaborate to cooperatively decide on charge transfers between potential transfer partners individually [23, 26]. Despite hardware capabilities enabling direct charge transfers between non-neighboring cells, all decentralized strategies currently only operate between neighboring cells. Therefore, an open research problem is the design of decentralized strategies between non-neighboring cells, which promises to further increase the balancing efficiency.

5.2 System Architecture Simulation and Analysis Tools

When designing complex battery system architectures, building a hardware setup at full scale is usually not possible for pack-level development. Therefore, simulation and analysis frameworks are needed such that design automation tools can be leveraged as far as possible in the design process. A holistic design flow could follow the general modeling hierarchy introduced as a cyber-physical co-simulation framework focused on battery systems [23]. Here, on each level of the system architecture, starting at the cell level up to the algorithmic level, advanced modeling tools can be utilized. In order to speed up the design process, e.g., a framework for rapid analysis of active cell balancing circuits was introduced in [27]. With the options on battery system architecture design becoming more complex due to the emerging requirements of modularity, connectedness and scalability, design flows enabling automation become more important. In the domain of smart battery cells, a design and verification methodology was presented in [28].

Future design automation techniques: With the individual building blocks for design automation of battery systems and their management methodology outlined in this section, it now becomes feasible to integrate them into a holistic design automation framework for battery systems, covering all levels of abstraction and enabling an automated design process of highly optimized battery systems. With the emerging degrees of freedom in designing optimized battery systems with reconfiguration possibilities and decentralized self-organizing control schemes, only with efficient design automation techniques, optimized design flows can be enabled.

6 CONCLUDING REMARKS

Electrical Energy Storage (EES) systems, specially in the form of high power Li-Ion battery packs, are an essential component for the successful deployment of renewable energy sources and alternative transportation technologies such as EVs and HEVs. Such battery packs are complex Cyber-Physical Systems (CPSs), where the physical parameters of the battery cells and the management algorithms that form the cyber part ensuring safe and efficient operation are designed in a tightly integrated fashion. In this paper, we presented a detailed overview of the different components involved in the battery systems from a design automation perspective and explained the existing tools in the literature that address some of the challenges present at each abstraction level of the battery system. However, with state-of-the-art battery systems trending towards a decentralized architecture owing to increased scalability and reduced time-to-market, it is critical to address the challenges involved in these distributed architectures. This requires a special set of design automation techniques and tools that could be developed from the existing approaches explained. This paper provided a concise overview of the challenges existing in the domain of battery systems and guides the scientific community to focus on developing future design automation tools that will enable design of highly optimized battery systems.

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