Distributed Reconfigurable Battery System Management Architectures

Sebastian Steinhorst[1], Zili Shao[2], Samarjit Chakraborty[3], Matthias Kauer[1], Shuai Li[2], Martin Lukasiewycz[1],
Swaminathan Narayanaswamy[1], Muhammad Usman Rafique[2], Qixin Wang[2]

[1] TUM CREATE Ltd., Singapore, Email: sebastian.steinhorst@tum-create.edu.sg
[2] The Hong Kong Polytechnic University, Email: cszlshao@comp.polyu.edu.hk
[3] TU Munich, Germany, Email: samarjit@tum.de

***Abstract*—This paper presents an overview of recent trends in Battery System Management Architectures (BSMAs). After introducing the main characteristics of large battery packs, the state of the art in BSMAs is discussed. Two emerging concepts are in the focus of this contribution. On the one hand, there is a development from centralized battery management architectures with a single control entity towards decentralized management where the computational resources are distributed across the battery pack and, hence, move closer to the individual battery cells. This enables a more scalable and modular battery system architecture, while, at the same time, posing challenges regarding hardware and management algorithm design. On the other hand, the static setup of the series- and parallel-connected cells forming the battery pack may be developed towards a reconfigurable architecture such that the electrical topology of the pack can be adaptively changed. Such reconfigurability could increase the reliability of battery packs and reduce management efforts such as cell balancing. At the same time, limited energy efficiency of the additional hardware poses a challenge. We give an outlook how these two trends could be combined into distributed reconfigurable BSMAs. This introduces a set of challenges which have to be solved in order to benefit from the increased scalability, reliability and safety such designs could offer.**

I. INTRODUCTION

Large battery packs are a central component of emerging technologies such as Electric Vehicles (EVs) and stationary energy storages for smart grids. They comprise battery cells in a series and parallel electrical connection to achieve a certain voltage and capacity. Here, a series-connection of cells increases the pack voltage, while parallel-connecting cells increases the capacity and possible maximum pack current. Layers are first formed from parallel-connected cells and these layers are then series-connected. A common terminology specifying a battery pack architecture with respect to the organization of cells is to state the number of cells in series and in parallel, e.g., 96S74P would define the architecture of a Tesla Model S electric vehicle battery pack where 96 series-connected layers are employed and each of the layers consists of 74 cells in parallel.

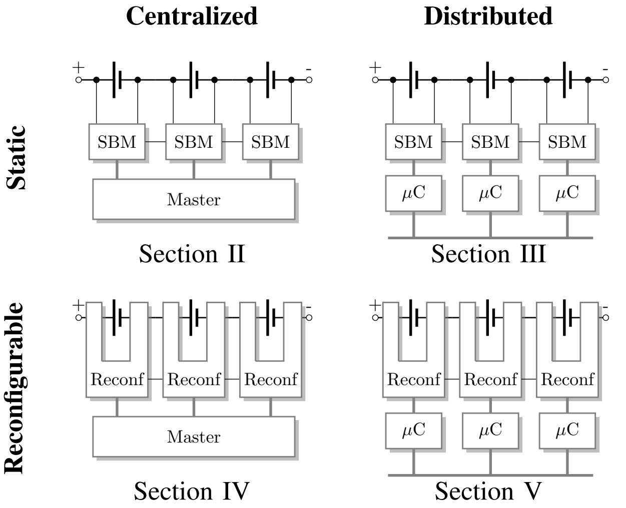

Fig. 1: Recent trends in Battery System Management Architectures (BSMAs) can be categorized in two dimensions. State-of-the-art architectures are centralized regarding the Battery Management System (BMS) and static regarding the cell topology. Distributed and reconfigurable architectures are investigated in the scientific community.

Lithium-Ion (Li-Ion) Battery Characteristics. Due to its high power- and energy density, Li-Ion is the battery chemistry used in most applications where weight and size of the battery pack are critical. While the price per kilowatt hour (kWh) of storage capacity is more expensive for Li-Ion battery packs, Li-Ion dominates practically all other chemistries such as Lead-Acid or Nickel-Metal Hydride (NiMH) regarding power and energy density. Moreover, Li-Ion batteries have almost no memory effect, which means that they can be charged to full capacity regardless of their current State of Charge (SoC) and without dependency on previous charging cycles. Additionally, they have a very high cycle life, resulting in thousands of charge-discharge cycles until the battery performance fades significantly. Due to these beneficial properties and their wide application, in the remainder of this paper we only consider Li-Ion battery chemistry for the cells in the presented battery systems.

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Battery Management. Li-Ion cells are very sensitive with respect to their operating parameters. Operating cells out of strictly specified voltage, current and temperature ranges can cause critical damage to the battery cells and lead to thermal runaway, a condition where the cell enters an irreversible chemical reaction resulting in fire and possible explosion. Consequently, Battery Management Systems (BMSs) are required to monitor and control the battery packs such that all cells are never crossing parameter thresholds at any point in time.

Traditional tasks of BMSs are sensing of cell parameters and estimating the pack-SoC. Here, the pack-SoC is determined by the cell with the minimal amount of stored charge in the pack. Once the first cell reaches the bottom of its acceptable SoC range, discharging of the pack has to be stopped to prevent cells from getting damaged. Due to manufacturing tolerances and temperature variations, the SoC of cells in a series-string diverges over time. Consequently, to maximize the usable capacity of battery packs, cell balancing has to be performed which equalizes the voltage and, hence, SoC variation among cells. Note that cell balancing approaches are only required between the series-connected layers. All cells connected in parallel are balancing themselves permanently and hence can be considered as electrically indistinguishable. Therefore, all further discussions and illustrations referring to a single cell also apply to a parallel connection of several cells.

Battery System Management Architectures (BSMAs). Beyond BMSs, which comprise sensing, control and computational capabilities, we extend the scope of this paper to BSMAs, which also cover the design of the electrical interconnection of cells and cyber-physical aspects of battery management. Traditionally, BSMAs have been designed in a static fashion where the topology of the series and parallel-connected cells has been fixed. Additionally, the hardware/software architecture has been organized in a centralized fashion. However, recently, some new directions have been investigated in literature, both in terms of architectures as well as management policies. So far, there has been no systematic classification of these works as well as a comparison of the features, advantages, disadvantages and challenges of the presented approaches. Consequently, in this paper, we propose a classification and discuss different aspects of architecture and management approaches.

BSMA Classification. The classification we propose is based on two main trends we have identified in the BSMA domain. Firstly, centralized battery management architectures with a single control entity are getting replaced by decentralized management, distributing sensing, control and computational resources across the battery pack. Secondly, static electrical setups of the series- and parallel-connected cells in battery packs could be replaced by reconfigurable architectures such that pack configurations can be adaptively changed. We illustrate the classification along two dimensions into four classes in Figure 1 which also determines the organization of this paper. For an explanation of the individual architecture components of the four classes, please refer to the respective sections.

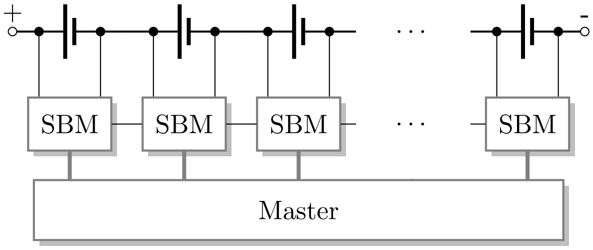

Fig. 2: Centralized management setup with a static electrical connection of the cells representing state-of-the-art BSMAs. Voltage and temperature are sensed per cell by a Sensing and Balancing Module (SBM) and processed by the central Pack Management Unit (PMU) as master controller. It also controls passive cell balancing performed by switched resistors across each cell.

One dimension is classified into centralized and distributed. The other dimension is classified into static and reconfigurable. The first class represents the state of the art, comprising a centralized static BSMA. This conventional architecture, together with relevant literature, is discussed in Section II. The second class changes the control from centralized to distributed with a static electric topology. This distributed static architecture is discussed in Section III. The third class enables reconfiguration of the electrical topology while maintaining a centralized control. This centralized reconfigurable architecture is discussed in Section IV. Finally, the fourth class considers BSMAs that are both distributed and reconfigurable. We give an outlook on the key performance aspects and design challenges of this architecture in Section V. Concluding remarks are given in Section VI.

II. STATE OF THE ART: CENTRALIZED STATIC

The established design approach and management architecture of large battery packs relies on a static pack topology for the electrical connection of the battery cells, such as described for the Tesla Model S battery pack in the introduction. With electrical connection, we specifically refer to the power line that carries the main pack current. In this context, the focus for such pack architectures is on the BMS which monitors and controls the parameters of the battery pack such that it stays in a safe and healthy state.

BMS Hardware Architecture. As illustrated in Figure 2, there is a means to sense voltage across each individual cell for monitoring purposes. Temperatures within the pack are also monitored, preferably per cell. Current measurement in a series-connected string is required only in one location and is usually performed within a special module using a hall-effect sensor. The Sensing and Balancing Modules (SBMs) can be present either per cell or for cell stacks of up to 12 series-connected cells in form of Module Management Units (MMUs). The SBMs or MMUs are controlled by the master controller in a hierarchical fashion. The master controller is also referred to as Pack Management Unit (PMU).

Scalability Challenges. From a software perspective, the PMU provides information on the status of the pack to other entities and processes tasks such as SoC estimation by sampling the information from the cells in appropriate intervals depending on the usage scenario. Scalability of this centralized architecture is limited, regarding both hardware and software integration. Depending on the application scenario and the chosen SBM or MMU, the software on the PMU has to be significantly adapted beyond parameterization for the specific cells. In addition, the PMU hardware has certain fixed computational and input/output performance that does not scale with the amount of cells in the pack. Hence, the PMU has to be specifically chosen for a certain application in order to either avoid costly underutilization or safety risks from underperformance.

State-of-the-art Implementations. Covering mechanical design, thermal aspects and battery management, a discussion of challenges with regard to battery pack design is presented in [1]. A comprehensive overview of state-of-the-art BMS design and architectures from an EV perspective is given in [2] and [3], respectively. The specific challenges of managing large battery packs with a focus on the properties of Li-Ion batteries are discussed in [4].

Passive Cell Balancing. For the important function of cell balancing, state-of-the-art architectures almost exclusively use passive cell balancing. Here, the SoC of all cells is reduced to match the one of the cell with the minimum charge in the battery pack [5], [6]. This is usually achieved using an individual switched resistor across each cell such that the stored excess energy can be dissipated. While this approach is simple to implement and control, dissipating energy across resistors is highly inefficient.

III. DISTRIBUTED STATIC

With the perennial demand for shorter time to market, integration aspects of battery packs are moving into the focus of BSMA design. Conventional centralized designs, as discussed in the previous section, cannot provide plug-and-play integration and are not sufficiently scalable. Consequently, with more applications for battery packs emerging, managing the design and integration effort of battery packs requires a paradigm change towards novel architectures. These architectures are specifically designed such that the focus is on maximizing scalability and minimizing integration efforts.

Decentralization Approaches. While still keeping a lightweight central master controller, the concept presented in [7] proposes to use individual cell modules that integrate sensing, cell balancing, local computation and communication. In this context, a contact-less communication approach can enable simple hardware integration and scalability [8]. The architecture presented in [9] is characterized by completely decentralizing the BMS architecture as illustrated in Figure 3. Therefore, no central controller is present in this self-organizing adaptive architecture. By incorporating both the SBM and a microcontroller with a communication interface into each individual cell, an autonomous Cell Management Unit (CMU) is formed that permanently manages all properties of the cell it is attached to. Pack-level functions such as cell balancing or pack-SoC estimation are performed in a cooperative fashion between the cells by using the provided communication channel.

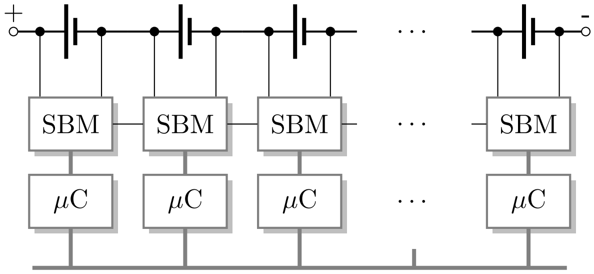

Fig. 3: *Fully distributed "Smart Cell" management architecture with a static electrical pack topology. A Cell Management Unit (CMU) is formed by the SBM and a microcontroller, providing local control, computation and communication resources.*

Benefits of Architecture Decentralization. Approaches to achieve the aforementioned integration goals are characterized by moving the battery management hardware, including computation, as close to the cells as possible. Consequently, the BMS is distributed across the battery pack and the individual nodes are coordinated via a communication channel. This enables homogeneous modules for simple hardware integration. The design paradigm for these modules, also called *Smart Cells*, is that scaling of the battery pack to the size required for different applications shall neither require changes in the hardware nor the software of the modules. Furthermore, the single point of failure of centralized approaches is avoided. Using algorithms from the domain of self-organizing systems, a customization-free plug-and-play integration can be achieved which does not require a central master controller. Here, the local control of each cell by the CMU additionally increases the safety of the battery pack. Sensor information has to be processed only for the local cell and possible actions can be triggered instantaneously by the CMU.

Suitability for Active Cell Balancing. In the context of the important function of charge equalization, the decentralized system architecture can enable an efficient implementation of modular active cell balancing architectures. In contrast to the passive balancing approach discussed in the previous section, active cell balancing can transfer charge between cells, usually using temporary energy storage modules such as capacitors, inductors or transformers in a switching network. This is significantly increasing the energy efficiency of the balancing process as charge is transferred instead of dissipated. The complex control patterns required for the Pulse Width Modulation (PWM) signals actuating Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) switches of such active balancing circuits are very difficult to generate and distribute from a central controller. With the modularization into a CMU, the PWM generation can, however, be performed locally at cell level. This makes modular active balancing architectures such as those proposed in [10], [11], [12] more manageable and hence applicable.

Second Life. With a CMU attached to each cell for the whole lifetime, *second life* applications are facilitated. Second life for battery cells is referred to as the reuse of cells, which do no longer meet the requirements of their initial application, in a less demanding environment. Cells from EVs could, for instance, be employed in a stationary energy storage for renewable energy in households where volume and thus energy density is less critical. Identifying the individual parameters of used cells is costly for conventional architectures such that the cells are rather recycled. By contrast, with the performance data accessible and uniquely assigned to each cell via the locally available CMU, the selection of cells for second life applications as well as their management becomes feasible.

Algorithmic and Communication Challenges. The decentralization of the system architecture requires a paradigm shift from an algorithmic perspective. Without a central master controller, actions are performed by negotiations between the Smart Cells in a distributed fashion. If the communication architecture is a bus, managing the amount of messages required for performing the required negotiations covering all BMS functions is critical. While broadcasts, such as cell-SoC communcation, are fast, operations involving only local properties between neighbors occupy the bus equally and filtering has to ensure that the communication stays efficient. Furthermore, obtaining information on the topological order of the Smart Cells can be a challenging task [13]. By contrast, a daisy chain communication enables concurrent and local communication. Broadcasts, however, are time-consuming as messages have to propagate the whole chain of connected cells. Here, a new class of algorithms that transfers centralized battery management functions into a distributed mode of operation is required and poses interesting design challenges.

CMU Integration. Together with the distributed algorithm design, miniaturization of the CMU and the active balancing circuitry poses a challenge. Eventually, a cell-integrated system-on-chip is envisioned that can outperform existing centralized approaches regarding cost, efficiency and pack integration aspects. Certain design challenges from a circuit design perspective have to be solved such as minimizing power consumption of the CMU. This requires highly efficient design and manufacturing process solutions for the on-chip power supply, the computational core, the balancing circuitry and the communication interface, which has to deal with the different potentials of the different CMUs when connected in a bus fashion. Together with the mandatory temperature sensors, in-situ implementations of the CMU within the cell casing could be considered.

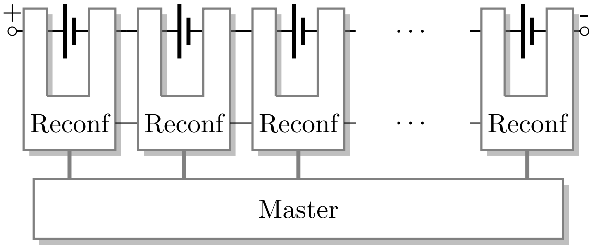

Fig. 4: Reconfigurable electrical topology in a BSMA with a central management setup using a master controller. The reconfiguration allows to change the electrical topology such that cells can be connected in series or parallel. Moreover, bypassing of cells is enabled by the reconfiguration circuitry.

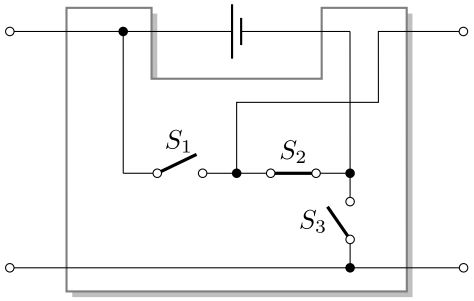

Fig. 5: Single cell-level module of the reconfigurable architecture, consisting of three switches per cell as proposed in [14]. With S_2 closed, the modules are in a series connection.

IV. CENTRALIZED RECONFIGURABLE

In this section, we explain the centralized reconfigurable BSMA which is characterized by a reconfigurable electrical topology but controlled by a central master. The reconfiguration enables setting up different series-parallel connections of arbitrary cells in the battery pack.

Reconfigurable system architecture. A system-level representation of the centralized reconfigurable architecture is shown in Figure 4 and the individual cell-level reconfigurable block is shown in Figure 5. Each cell-level reconfigurable module consists of three switches as proposed in [14], that are either open or closed at any given point of time. Using an appropriate switching scheme, the master controller in the centralized BSMA can isolate a cell from the main power line or connect arbitrary cells in either series or parallel depending upon the load requirement.

Benefits of Reconfiguration. Connecting parallel-connected cell modules in series (Parallel-Connected Module (PCM)) or series-connected cell strings in parallel (Series-Connected Module (SCM)), as explained in [15] and [16], has individual advantages and disadvantages. The PCM battery topology does not require balancing circuitry for the parallel-connected cells, since they equalize themselves and by connecting cells in parallel, the influence of statistical variation between individual cells is minimized. However, this topology suffers from decreased energy efficiency if one of the cells in the parallel-connected module exhibits a short circuit fault. On the other hand, the SCM topology allows to increase the capacity of an existing pack by adding another series string, without requiring extensive modification to the existing system. Nevertheless, the constant intra-string currents due to cell variations impact the lifetime of the battery pack. Here, the flexibility offered by the reconfigurable architecture to choose any cells to be connected in series or parallel allows to utilize only the benefits of both topologies, mitigating their disadvantages.

For Electrical Energy Storage (EES) systems used in smart grid applications, the varying load demand during peak periods of operation requires different operating voltage, current and power. This could be satisfied with a reconfigurable battery pack which has the ability to connect arbitrary numbers of cells in either series or parallel to increase the voltage or capacity, respectively. Moreover, the capability to isolate individual cells from the main power line can be used during the charging process to bypass cells that are fully charged before other cells in the battery pack. Here, the reconfiguration feature can also be used to improve the State-of-Health (SoH) of the battery pack by connecting cells with similar SoH in series during charging/discharging. Likewise, cells with equal SoC can be connected in series by using the reconfiguration switching network to improve the usable capacity of the battery pack. Another benefit of the reconfigurable architecture is the possibility to reduce the discharge rate of stressed cells by connecting more such cells in parallel. This reduces the current through each cell in the parallel-connected block, consequently improving the lifetime of cells with a reduced SoH.

Existing implementations. A generic reconfigurable architecture is presented in [17]. In [14], a central controller is proposed which coordinates local slave controllers for the reconfiguration switches of each individual cell. The design explained in [18] models the reconfiguration network for varying load demands as a graph problem to obtain energy-efficient battery topologies. A reconfiguration method based on SoH is evaluated in [19] which increases the discharge time and capacity. Another variant of a reconfiguration switching architecture, as presented in [20] and [21], is used to optimally charge the battery pack considering the imbalances between the individual cells.

Challenges. With the existing reconfiguration architecture, cells can either be connected in series or in parallel or can be isolated from the main power line of the battery pack. However, connecting certain cells in parallel and then connecting the parallel modules in series or vice versa is not possible with the architecture shown in Figure 5. The addition of new switches to each module or increasing the interconnection points between the modules would achieve a higher flexibility to form a fully reconfigurable system architecture that can realize any desired battery pack topology. Here, the accurate estimation of SoC and SoH of each individual cell, on which the switching scheme for reconfiguration is determined, poses a challenge in the reconfigurable architecture.

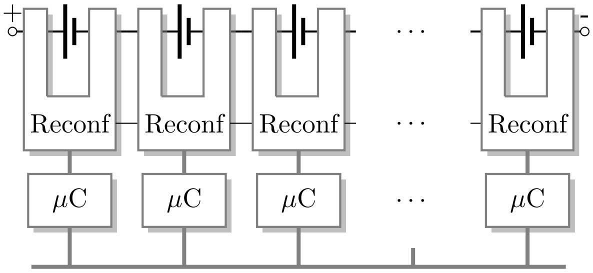

Fig. 6: BSMA with a reconfigurable electrical topology in a fully distributed management setup. Each reconfiguration module together with a microcontroller and a communication interface forms the CMU in this setup.

The physical size of the switches is a key challenge especially in terms of automotive applications, where low volume and weight are the key design factors. In this context, minimizing the ohmic losses in the reconfiguration switches is an important factor to be considered. Here, size and weight of the switches can be considered as proportional to energy-efficiency. Typically, Solid State Relays (SSRs) would be a preferred choice compared to electromechanical relays due to their fast switching times and improved lifetime because of no moving parts. However, due to their *ON*-resistance R, they have significant power dissipation given by $P = I^2 \cdot R$ when a current I flows through them. Therefore, developing switches with a low *ON*-resistance is critical to implement an energy-efficient reconfiguration system architecture for high power applications. With advances in semiconductor technology, it is expected that the *ON*-resistance of switches will be further reduced.

V. OUTLOOK: DISTRIBUTED RECONFIGURABLE

In the previous two sections, we have discussed the approaches to decentralize BSMAs and to enable reconfiguration possibilities. Both decentralization and reconfiguration have a set of benefits and come along with specific challenges. The combination of both decentralized control and reconfigurable electrical battery pack topology is illustrated in Figure 6 and would provide the benefits of both concepts once the individual challenges for either approach have been solved. In this context, a distributed reconfigurable BSMA consists of homogeneous modules that contain the battery cell, a reconfiguration circuit and a CMU that locally manages the properties of the cell, including the switches in the reconfiguration circuit. Consequently, the concept of Smart Cells has to be extended to control and exploit the reconfiguration capabilities.

Benefits of Distributed Reconfigurable BSMAs. The central control and actuation of switch configurations poses a challenge for centralized BSMAs. By contrast, with a local CMU available per Smart Cell, the problem of distributing hundreds of control signals across the battery pack would be solved. Here, the concepts of self-organization and collaborative system-level functionality available for the Smart Cells discussed in Section III would extend to the reconfiguration. Each CMU is locally responsible for control of the switches in the local reconfiguration module illustrated in Figure 5. Beyond collaboratively organizing the configuration according to external requirements such as voltage or capacity, this locally controlled reconfigurable BSMA can perform individual management actions on cell level, autonomously decided by each CMU.

A Smart Cell with reconfiguration capabilities can set the reconfiguration switches to bypass itself when it reaches its upper voltage threshold when charging or its lower threshold when discharging, respectively. This would be an alternative to conventional approaches to cell balancing. Furthermore, this local control of bypassing creates a significant safety benefit as the cell can immediately isolate itself from the pack when certain critical conditions are detected by the CMU. This safety feature can be further enhanced to cover defects in the CMU if the switches and their circuit network are designed such that the cell is isolated per default when no active control signals are created by the CMU.

Design and Implementation Challenges. The challenges of designing and implementing a distributed reconfigurable BSMA include the individual challenges discussed in Section III and Section IV. Beyond that, combining the Smart Cell approaches with reconfiguration circuitry poses further design challenges in the domain of power consumption and control algorithms.

The power consumption of the CMU increases as the reconfiguration switches have to be powered by local gate drivers which require individual DC-DC converters to achieve the required potentials. Permanently controlling the reconfiguration circuitry also reduces the idle time of the CMU, requiring sophisticated approaches to efficient design and power management. Here, a hardware-software co-design of both the software platform for the Smart Cells as well as their hardware platform is mandatory, especially considering the integration and control of reconfiguration circuitry.

Extending the self-organization properties for Smart Cells to cover all aspects of reconfiguration poses further challenges from the algorithm design perspective. While collaborative control of active cell balancing has been shown in a prototypic hardware setup in [9] for a fully distributed Smart Cell architecture, design of distributed algorithms for all other battery management functions, specifically including adaptive reconfiguration, poses many open research challenges.

VI. CONCLUDING REMARKS

In this paper we have discussed how state-of-the-art battery packs could be significantly improved by two recent trends in BSMA design. On the one hand, decentralization of the battery management architecture was discussed, illustrating the benefits of increased scalability and reliability, together with design challenges on the hardware and software levels. On the other hand, adding reconfiguration capabilities to the electrical battery pack topology can efficiently solve certain battery management problems such as cell balancing or isolation of defect cells, while introducing challenges stemming from the energy dissipation of the switches inevitably introduced into the main power line. Possible approaches to overcoming the design challenges to finally achieve a combination of both fully distributed as well as reconfigurable BSMAs were discussed. Once the presented design challenges are solved, distributed reconfigurable BSMAs might become the architecture of choice in future battery pack designs.

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