Smart Cells for Embedded Battery Management

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***Abstract*—This paper introduces a novel approach to battery management. In contrast to state-of-the-art solutions where a central Battery Management System (BMS) exists, we propose an Embedded Battery Management (EBM) that entirely decentralizes the monitoring and control of the battery pack. For this purpose, each cell of the pack is equipped with a Cell Management Unit (CMU) that monitors and controls local parameters of the respective cell, using its computational and communication resources. This combination of a battery cell and CMU forms the smart cell. Consequently, system-level functions are performed in a distributed fashion by the network of smart cells, applying concepts of self-organization to enable plug-and-play integration. This decentralized distributed architecture might offer significant advantages over centralized BMSs, resulting in higher modularity, easier integration and shorter time to market for battery packs. A development platform has been set up to design and analyze circuits, protocols and algorithms for EBM enabled by smart cells.**

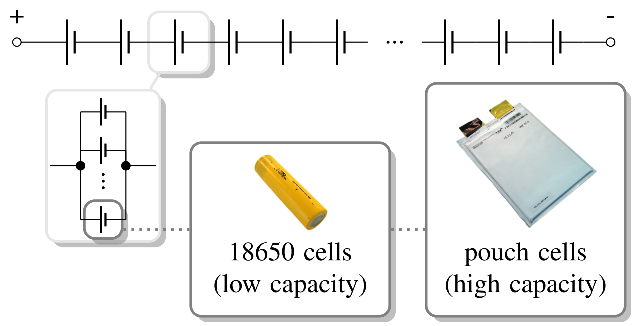

Fig. 1: Illustration of a battery pack architecture with cells connected in series. Each layer of cells might consist of multiple cells in parallel to increase the capacity. Individual cells could range from small 18650 cells to large pouch cells.

I. Introduction

With the transition from fossil to regenerative energy sources, as well as emerging Electric Vehicle (EV) and smart grid markets, Electrical Energy Storages (EESs) are gaining importance. While specific applications may require other EESs such as supercapacitors or fuel cell systems, electrical energy is commonly stored in batteries that consist of electrochemical cells. These battery cells are performing a reversible chemical reaction between their two electrodes, the positive cathode and the negative anode. This allows to charge and discharge cells multiple times by the movement of ions between the electrodes within an electrolyte. Consequently, an electrical current is flowing if the electrodes are electrically connected.

Battery packs consist of a number of series-connected cells as illustrated in Fig. 1. The pack voltage is the sum of the voltages of these cells in series. The maximum current which can be drawn from a cell is specified for each cell type. In order to achieve higher pack currents and capacities, cells can be connected in parallel in a module before these modules are wired in series. The energy storage capacity of parallel-connected cells sums up. For instance, for a cell with a nominal voltage of 4V and a capacity of 4Ah, first connecting two of these cells in parallel and then stacking them five times in series would result in a battery with 20V and 8Ah capacity, providing a 160Wh energy storage.

With its high power and energy density, Lithium-Ion (Li-Ion) battery technology is becoming the dominating cell chemistry for most EES applications from wearable electronics to stationary energy storages. Furthermore, in contrast to other battery chemistries such as Lead-Acid or NiCd, Li-Ion offers a higher number of charge-discharge cycles and is not sensitive to memory effects, where the charging cycle history influences the effective cell capacity. As an example, the Tesla Model S has an approximate energy storage capacity of 85kWh and voltage of 350V provided by 7104 Li-Ion cells of type "18650", with 96 cells in series and 74 in parallel.

Despite their significant advantages, maintaining the individual cells of a battery pack within a defined set of operating parameters is critical for Li-Ion batteries. Operation outside a specified range for temperature, cell voltage or charging/discharging rate can severely damage the cells, definitively reducing their lifetime and possibly causing fire or explosion by thermal runaway. Therefore, sophisticated battery management is required for battery packs, monitoring parameters of individual cells and controlling certain functions such as cell balancing. Recently, energy-efficiency has become a relevant design objective, as mobile EES are providing a limited amount of energy that translates into runtime of electronic devices or driving range in the case of EVs. Even for applications with periodic access to a power grid, energy-efficiency translates into cost-efficiency and environmental awareness by conserving energy.

Contributions of this paper. In Section II, we discuss conventional BMS architectures and their limitations. Conventional BMSs are organized in a centralized fashion where a master controller is sensing and controlling all properties of the cells. The master is either directly wired to each individual cell or slave modules form a hierarchy, handling the parameters of a set of cells. Despite the actual architecture, the master controller is the central instance where control decisions are made. This centralized architecture, however, brings several disadvantages that shall be overcome by the approach proposed in this paper.

We introduce the concept of Embedded Battery Management

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(EBM) in Section III where, in contrast to the centralized fashion of state-of-the-art approaches, a completely decentralized system is proposed. We discuss the general architecture and describe the tasks of separate components as well as requirements. The proposed approach enables system-level functionality without centralized control by coordinating individual actions via communication and distributed algorithms, offering a plug-and-play approach to battery pack integration.

The main component of EBM are smart cells which are discussed in Section IV. Smart cells have extensive autonomous capabilities, managing parameters of individual battery cells. Each smart cell consists of a battery cell and a Cell Management Unit (CMU) that comprises sensing, computation, control and communication capabilities. For functionality that requires information or control beyond the individual cell level, such as cell balancing or State-of-Charge (SoC) estimation for the battery pack, the smart cells communicate with each other, forming a distributed self-organizing structure that creates the behavior on the level of the battery pack.

In Section V, we present our development platform for EBM. The platform is an early prototype and used to validate the proposed concepts. In particular, the platform implements an active cell balancing architecture for charge equalization between the smart cells. This platform shall further serve for the design of distributed algorithms for battery management and CMU developments as outlined in the conclusion in Section VI.

II. Battery Management System (BMS)

This section discusses functions of state-of-the-art BMSs and their architectures.

While there are significant challenges already in the area of smartphone or laptop batteries, EV applications cover the largest set of demanding properties due to their requirement for high energy and power density with a high pack capacity. The goal is to offer an economical solution to minimize charging times and maximize the available energy while also maximizing the lifetime of the battery pack, guaranteeing safety and reliability of the system at run time. At design time, an efficient design of both the battery pack architecture and the BMS is desirable, allowing a fast integration of the battery into the application. In this context, [1] covers the state of the art of BMSs for electric vehicles.

A. BMS architecture

BMSs consist of components from two domains. The circuitry for sensing of the cell parameters, as well as the cell balancing architecture form the electrical domain. The electronic domain is formed by the computational devices that process the sensed information and control active functions such as cell balancing. Furthermore, a communication architecture is required in the electronic domain to connect the components of the BMS internally as well as with its surrounding systems.

Fig. 2 shows a typical state-of-the-art battery pack architecture with a centralized hierarchical battery management. Here, modules of cells are controlled by Module Management Units (MMUs) and the central BMS master is connected on a private communication bus to these MMUs to receive sensor data and to coordinate their actions. Moreover, a Current Sensor (CS) for measuring the battery pack current is employed.

First approaches to overcome centralized architectures are emerging. The approach in [2] proposes smart satellite systems

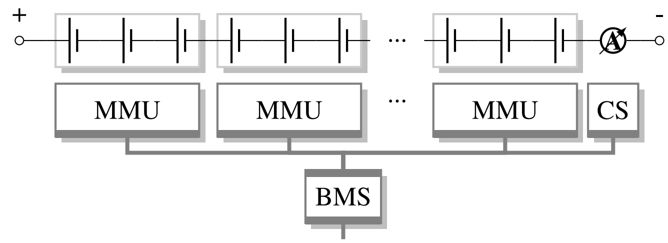


Fig. 2: Illustration of centralized battery management with a Battery Management System (BMS) master that controls Module Management Unit (MMU) slaves and a Current Sensor (CS) in a hierarchical architecture, see [1].

that monitor each module or each cell, still having a centralized control structure but targeting to decentralize parts of the BMS architecture. While cell balancing and basic sensing is performed directly at cell-level, a central main controller supervises the cells and controls the pack properties. In order to overcome the wiring harness of centralized BMSs, [3] proposes wireless communication between individual slave nodes and the master.

B. BMS functions

BMSs have to perform several different tasks, resulting in a broad range of functionalities covered by the system. An exhaustive overview is given in [4]. The most obvious function is computation of the SoC of the battery. Beyond that, every request to draw energy from the battery has to be checked against the power and discharge threshold of the cells, keeping them in a safe and healthy state.

The only direct sensor information that the BMS samples in short time intervals are the voltage and the temperature of each individual cell. The voltage of parallel-connected cells is equal and therefore only has to be acquired once. Whenever we will, in the remainder of this paper, refer to a cell, it can be either a single cell or a set of parallel-connected cells, as they are electrically indistinguishable and therefore managed as a single unit, see Fig. 1. Furthermore, the battery pack current is sensed, which is equal across the pack for all series-connected modules. Based on this information, the BMS has to compute the SoC of the individual cells and the overall battery pack, determining the remaining energy that can be drawn from the cells/pack.

The estimation of the SoC of the battery is a difficult task and many approaches have been proposed in literature. In [5] a comprehensive overview of the topic area and existing approaches is given. Here, the challenge is to determine an accurate estimation of the effective SoC of a battery or its individual cells without a direct way to obtain this value. Simple approaches just use a lookup table for the nonlinear relation of the open circuit voltage of the cell and its SoC. As such simple approaches are very inaccurate, sophisticated approaches such as Coulomb-counting try to keep track of all charge entering and leaving cells.

The State-of-Health (SoH) determines the overall status of the pack and a homogeneous degradation of the SoH is an indicator for an aging battery pack; degradation of the SoH of individual cells indicates faults. In this context, approaches to measure the internal resistance of the cells as an indicator of its SoH or performing impedance spectroscopy are employed [6].

Another important function of the BMS is cell balancing for maximizing the usable capacity of the battery [7], [8]. During charging and discharging of the series-connected cells in a battery, cells will, over time, have different SoCs. This distribution is due to variations in manufacturing and operating temperature that influence the capacity of each individual cell and the variation grows with every charging or discharging of the cells. As Li-Ion cells are very sensitive to minimum and maximum charge levels, certain thresholds for the SoC have to be maintained for every cell. If the SoC variation increases over time without performing countermeasures, the usable SoC of the battery pack is decreasing.

The cell with the lowest charge will require the whole discharging of the battery to be stopped once it reaches its lower discharging threshold. The same applies to charging where the charging process has to be stopped when the first cell reaches its upper SoC threshold. Therefore, cell balancing is performed to equalize the SoC of all cells in order to maximize the usable capacity of the battery pack. In the case of passive cell balancing [9], [10], only the upper SoC threshold of cells is considered. Therefore, this approach is only applicable when charging the cells. In order to maximize the battery pack SoC, the cells that have a higher individual SoC than others are discharged over a controlled resistor such that ideally all cells can reach their maximum SoC during charging.

Similarly, when the first cell in a battery pack reaches its lower SoC threshold, the discharging process has to be stopped as further discharging would harm the cell. There may be, however, a huge number of cells in the battery pack that have a slightly higher SoC. Although there is still energy available in these cells, the pack cannot be further discharged. Active cell balancing architectures [11], [12], [13] can utilize this remaining energy in some cells as charge can be transferred between cells. In contrast to passive cell balancing, where the SoC of cells can only be decreased, active cell balancing can increase the SoC of cells.

III. Embedded Battery Management

This section introduces our concept of completely decentralizing the BMS. Here, EBM describes a system architecture where the BMS functionality has been integrated into the cells that provide local sensing and management properties for themselves and the system-level functionality by coordination via communication.

A. EBM architecture

Fig. 3 depicts the proposed EBM architecture where every cell is attached to an individual Cell Management Unit (CMU) consisting of sensing and control circuitry as well as a computation and communication unit integrated with the cell. Such an integration of a cell with a CMU, enabling local management and distributed coordination, forms a *smart cell*. The network of smart cells performs the battery management in a cooperative manner. Note that smart cells and CMUs are discussed in detail in Section IV.

Network architecture. An individual smart cell can acquire and communicate information about its status and control certain local properties such as cell balancing. In order to create a battery pack out of smart cells that, from the outside, behaves as a conventional battery with all functionality required for a state-of-the-art BMS, the smart cells have to communicate with each other and cooperate to satisfy these pack-level requirements. For this purpose, a distributed system is obtained by the individual contributions of smart cells. Smart cells also require the capability to uniquely identify themselves in the network. In summary, the entity of a battery pack is formed by the smart cells adaptively, negotiating system-level parameters such as the number of available cells, overall battery pack capacity, cell balancing, as well as SoC and SoH.

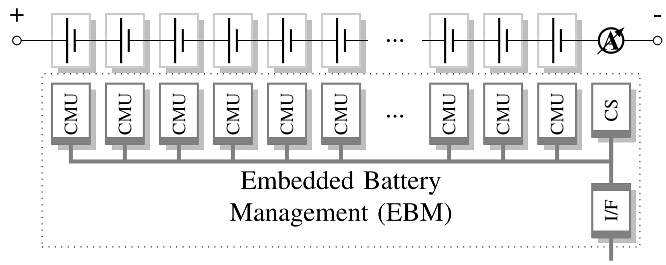


Fig. 3: Embedded Battery Management (EBM) architecture. Each cell is connected to a Cell Management Unit (CMU) that performs local sensing and control, computation and communication with other CMUs, enabling a distributed battery management. Additional components in the EBM are the Current Sensor (CS) and an interface unit (I/F).

For these distributed tasks of smart cells, a robust and reliable network architecture is necessary. At the same time, the wiring has to be kept at a minimum in order to ensure the low integration efforts that are promised by the EBM approach.

As cells are connected in series in battery packs, linear communication topologies are the most obvious solution. While Fig. 3 depicts a bus communication architecture, a daisy chain topology might also be feasible. Both approaches have various advantages and disadvantages in terms of communication bandwidth, overhead and latencies.

Furthermore, wireless communication is a possible candidate for the network of smart cells as it further reduces integration efforts. However, a major drawback might be the unpredictability of wireless communication. Finally, hybrid architectures with wired and wireless communication could be a sustainable solution for EBM.

Pack-level current measurement. Measuring the current flow for each cell individually is not efficient, as in a series-connection of cells, the current will be the same for all cells. Therefore, only one current measurement is required in the EBM architecture for acquiring the pack current which then also applies to every cell. Consequently, this measurement needs to be broadcasted to all smart cells. Current measurement, however, is critical for determining the SoC of the cells, as certain Li-Ion cells have a very flat discharge voltage curve. For an accurate SoC estimation, integrating the current is mandatory. With the current flow over time in relation to the voltage of the individual cells, the remaining charge of a cell can be calculated by subtracting the drawn charge from the initial amount after being fully charged. This process is referred to as Coulomb counting.

Current can be measured either using a shunt resistor or a hall effect sensor. For pack-level current measurement, hall effect sensors give higher accuracy and energy efficiency. Dual-range devices are state-of-the-art in EV applications where a wide current range has to be covered with very high maximum currents up to 180A. For battery packs of these dimensions, a dedicated separate CS unit should be placed in the battery pack with a communication interface to send the current readings to the smart cells. In smaller battery packs with lower maximum currents, however, using a shunt resistance integrated into the CMU can be considered.

Communication interface. In order to provide information such as the SoC of the overall battery to other devices such as any Electronic Control Unit (ECU) in a vehicle or to receive commands and status information, a communication interface must be provided that links the internal network of the EBM architecture to an external communication channel. From a hardware perspective, this interface has to be compatible with the internal EBM network and the one of external devices and capable of forwarding messages between both channels.

B. EBM integration

The EBM architecture enables a plug-and-play design of battery packs, eliminating the electronic integration and only requiring a mechanical and electric integration of the homogeneous smart cells. Centralized BMS architectures require wiring of sensors between the cells and the central controller, introducing significant wiring harness as well as limiting architectural flexibility. For each application, the BMS has to be planned, the wiring determined and the specific parameters of the pack and the cells have to be implemented in the algorithms. By contrast, for the EBM approach, both architectural as well as spatial modularity is achieved by the homogeneous architecture of the smart cells that does not require a specific setup and can be spatially distributed as long as the power line, the communication connections and appropriate thermal conditions are provided.

IV. Smart Cell

The device enabling EBM is the smart cell and its architecture is introduced in the following.

A smart cell provides the functionality to monitor and control itself, as well as to send and receive messages for organizing battery-level functions in cooperation with other smart cells. The CMU attached to the cell is powered by the cell itself. Fig. 4 illustrates how a battery cell and the CMU are forming a smart cell. Here, the CMU comprises

- a sensor (voltage, temperature, current) and control board to acquire the parameters of the cell and perform cell balancing,
- computation capabilities in form of a microcontroller and
- a communication interface to exchange information between smart cells.

The amount of control circuitry that can be embedded into the CMU depends on the choice of which kind of cell balancing the smart cell shall support.

A. Sensing and Control

Voltage and temperature sensing. The basic properties of a cell are its present voltage and temperature. Furthermore, the current flow into and out of the cell has to be monitored. Both voltage and temperature sensing can be easily enabled by an integrated multiplexed Analog-Digital Converter (ADC) that is connected to the cell terminals on one channel and to a thermistor or resistance temperature detector on the other. Typically, Li-Ion cells have an usable voltage range between 2.7V and 4.2V. In order to have a resolution of 1mV, at least

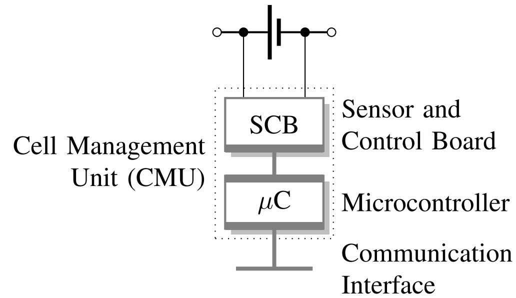


Fig. 4: A battery cell and its dedicated CMU form a smart cell. The CMU contains a sensor and control board, a microcontroller and a communication interface.

12 bit resolution is required for the ADC. Maximum sampling rates required for voltage sensing are in the 10 to 100 ms range, which can be covered by several types of ADCs.

Current sensing. Besides the pack-level current measurement, which has been discussed in Section III, cell balancing currents have to be measured. For both passive and active cell balancing, keeping track of the energy either dissipated or transferred is required for SoC determination. As in this case only the balancing current, which is low compared to the pack-level load current, has to be measured, a shunt resistor can be sufficient and cost-effective while hall effect sensors are the better choice when accuracy and efficiency requirements are dominating over cost and integration space.

Cell balancing. All smart cells that form a battery must have the same type of balancing capabilities. For passive cell balancing, the CMU must contain a switchable resistor that can dissipate energy stored in the cell. For active cell balancing, a modular inductor-based architecture such as the ones proposed in [11] or [12] are suitable, as they consist of homogeneous modules that can be integrated into each smart cell.

B. Computation

The architecture of EBM using smart cells requires the CMU to perform computational tasks to process local information from the sensors of the smart cell as well as information received via the communication channel the smart cell is connected to. Based on this information processing, the management and control of the individual cell as well as the cooperative system-level functionality, to which the smart cell contributes, has to be performed.

As the CMU is powered directly by the cell it is attached to, low-power processing is the main objective when choosing an appropriate computational core. Nevertheless, the computational capabilities have to satisfy the requirements of local calculation of the SoC and SoH of the cell with a sampling rate of the sensor data of up to 100 Hz. Furthermore, the communication with other smart cells has to be provided where the cell may have to receive and process hundreds of messages per second with status and control information from other cells when considering an EV battery where approximately 100 smart cells are connected in series.

C. Communication

The communication architecture to chose in order to connect the smart cells is a complex design challenge. Traditionally, a

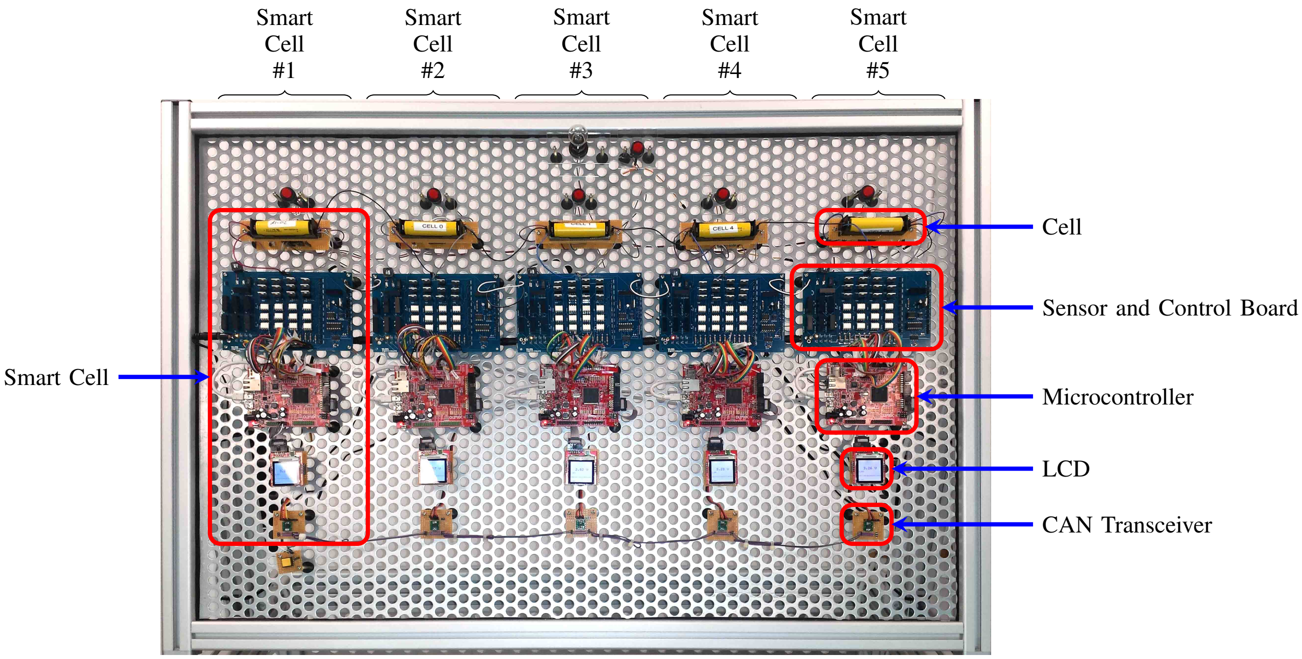


Fig. 5: Development platform for EBM. Five cells with individual sensor and control board and microcontroller form five smart cells, communicating via a CAN bus.

wired bus would be a reliable and well understood choice. Here, the emphasis is on broadcast messages with only one smart cell transmitting to the bus at a time. Furthermore, message filtering has to be performed, such that smart cells can decide whether they have to process a message. This is, however, coming at the cost of energy consumption that occurs in every node whenever a message is sent on the bus. Therefore, a daisy chain topology could be considered. Here, broadcasts are expensive as messages have to be relayed across all nodes. Local communication with neighboring nodes can, by contrast, be performed concurrently, allowing for local parallel communication. Wireless networks as well as powerline networks can be considered beyond conventional wired communication bus architectures. These communication approaches would bring the benefit of further decreasing wiring efforts of the integration. Note that wireless communication, as well as powerline communication, are generally organized in a bus fashion. Here, requirements for reliability and robustness of the communication have to be ensured, as the environment can have an impact on the performance of the communication system.

V. Development Platform

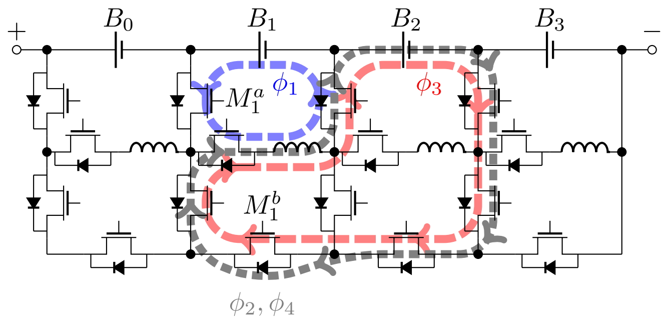
This section introduces our development platform for EBM shown in Fig. 5.

Hardware architecture. The development platform consists of five smart cells that are each formed by using a 18650 Li-Ion cell that is connected to a sensor and control circuitry board. The sensor and control board is operated by a STM32F407 microcontroller board running a Micrium µC/OS-III real-time operating system for the distributed control algorithms. The communication between the smart cells is performed via a CAN bus connecting the microcontroller boards. Consequently, the boards for sensing and control, microcontroller and CAN communication logically form the CMU.

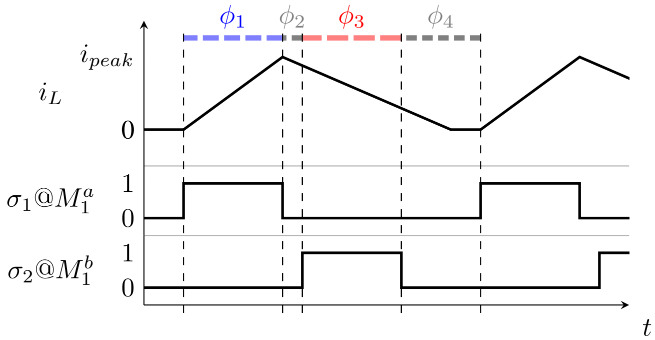
A light bulb serves as a global load and individual resistive loads for each smart cell allow to influence the SoC of the cell. Furthermore, a LCD display is connected to the microcontroller in order to show status parameters of each smart cell such as a scope view of the current cell voltage and other parameters. Each of the five columns consisting of cell, sensor and control board, microcontroller board and communication interface represents a smart cell. For research purposes, we decided to first develop an architecture that is as universal as possible for exploration of the characteristics and possibilities before starting integration towards space reduction.

Cell balancing. The sensor and control board is capable of performing concurrent inductor-based active cell balancing between non-neighboring cells, allowing high-efficiency charge transfer. We have designed it as a development board that can model various inductive balancing architectures by setting some of the switches to be constantly closed. It uses an inductor, 12 power Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) with driver circuits and is equipped with voltage, temperature and current sensors that are connected to the microcontroller via an ADC using Serial Peripheral Interface (SPI). For instance, the balancing architecture in Fig. 6a is based on four MOSFETs per cell and it is obtained by setting eight MOSFETs to be constantly closed.

The balancing requires the control of some MOSFETs using Pulse Width Modulation (PWM) signals. Generation of proper PWM signals from the microcontroller is challenging as they have to be processed concurrently while other tasks are performed. This is only possible using hardware timers of the microcontroller architecture. Due to the limited number of timers and their shared I/O pins with other functions such as SPI, PWM generation has to be considered under significant constraints. As an initial proof-of-concept, we have modeled an architecture with four MOSFETs per cell on our development board. Fig. 6a shows the equivalent circuit schematic



(a) Balancing circuit configuration



(b) Control scheme and resulting inductor current

Fig. 6: Balancing architecture configuration for charge transfer between neighboring cells via an inductor. The transfer is carried out in four phases ϕ_1 to ϕ_4 where appropriate PWM signals σ_1 and σ_2 are applied to the MOSFETs.

which is configured on the development board and Fig. 6b illustrates the required periodically occurring phases ϕ_1 to ϕ_4 of the non-overlapping PWM signals which control the MOSFET switches. Here, in phase ϕ_1, the inductor is charged from cell B_1 by closing M_1^a and discharged into cell B_2 in phases ϕ_2 to ϕ_4. Phases ϕ_2 and ϕ_4 are created by the non-overlapping behavior of the PWMs, using freewheeling diodes in the MOSFETs to prevent short circuits when M_1^b is closed. Note that the architecture of our development board allows to achieve a configuration where all PWM-operated MOSFETs are controlled by a single smart cell. More complex balancing architectures may, however, require synchronization of PWM phases across smart cells.

Cell balancing is both a very important BMS function as well as a good test case for distributed algorithms. Here, knowledge about the SoC of all cells is required for determining optimal partners for charge transfer. This assignment of balancing partners has to be negotiated between the individual smart cells. Balancing can comprise simple policies where the weakest cells are iteratively receiving charge from those with above-average SoCs, up to considering the charge transfers as an optimization problem such that the energy dissipation during cell balancing is minimized.

Software architecture. We have implemented a software architecture where the smart cells organize themselves after power-on, performing active cell balancing whenever necessary. The first step of self-organization is the identification of the number of available smart cells in a battery pack and creating a topological order. This order is required for functions such as charge transfer, where individual cells have to know their position in the series string of cells and those of their charge transfer partners. The smart cells monitor their local SoC and exchange this information with other smart cells. From this information, balancing partners are negotiated such that the SoC of all cells is maintained equal by transferring charge between the balancing partners. Due to the completely distributed architecture, this functionality is performed without a fixed central controller as it would be present in conventional BMS architectures.

VI. Concluding Remarks

In this paper we have proposed a completely decentralized and distributed approach to battery management. The architecture of Embedded Battery Management (EBM) consists of smart cells that perform autonomous local management on cell-level and coordinate pack-level functions using a communication system. Each smart cell consists of a battery cell and a Cell Management Unit (CMU) providing sensing, control, computation and communication capabilities. This leads to a plug-and-play integration of battery packs consisting of self-organizing smart cells, introducing spatial modularity and flexibility as well as enabling shorter development times. Our development platform for EBM is capable of negotiating and performing cell balancing between smart cells, proving the feasibility of the approach.

Future work comprises development of distributed algorithms for all BMS functions, integrating the CMU hardware and minimizing the energy consumption on circuit, computation and communication level.

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