Scalable, Decentralized Battery Management System Based on Self-organizing Nodes

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Abstract. Due to the transition to renewable energy sources and the increasing share of electric vehicles and smart grids, batteries are gaining in importance. Battery management systems (BMSs) are required for optimal, reliable operation. In this paper, existing BMS topologies are presented and evaluated in terms of reliability, scalability and flexibility. The decentralisation of BMSs and associated advantages are shown. A scalable, reconfigurable BMS based on a distributed architecture of self-organized, locally controlled nodes is proposed. For distributed system control, producers, batteries and consumers each are equipped with a local microcontroller based control unit, which monitors and controls the local parameters with its own computing and communication resources. Features, advantages and challenges to overcome of the proposed approach are described.

Keywords: Renewable energy sources · Battery management systems · Multi-microcomputer system · Topology · Scalability · Reconfigurable architectures · Availability · Decentralized control · Fault tolerant control · Controller Area Network · Distributed management

1   Introduction

With an increasing share of renewable energy sources and electric vehicles, batteries are one of the most utilized energy storage media [1]. Battery use is essential for maintaining the energy balance and for improving the quality as well as the reliability of power supply in renewable energy systems [2]. A critical challenge facing the widespread adoption of battery technology is to ensure uninterrupted, fail-safe power supply and safe, optimal battery operation to extend battery life. Battery Management Systems (BMSs) are used for these purposes and provide the interfaces between energy producers, consumers and batteries (Fig. 1). They administer system control and management with regard to

energy storage and transmission. Main functions of the BMS include charge and discharge control, balancing, input/output current and voltage monitoring, temperature control, battery protection, fault diagnosis and evaluation [3].
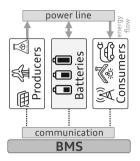

Fig. 1. Principle architecture of a BMS indicating participants, communication and power flow

For this purpose, the following functional requirements are relevant for a BMS:

– Current, voltage and temperature measurement
– State of charge (SOC) and state of health (SOH) determination
– Communication
– Robustness against electromagnetic interference (EMI)
– Redundancy of the system in terms of functional safety
– Electrical isolation of the functional systems
– Balancing [4,5]

Besides the BMS unit, which includes data acquisition, status monitoring and control, the topology of the BMS is crucial for large-scale battery management. The topology covers the electrical connection of the individual batteries or battery cells, the control structure and the communication architecture. It directly influences costs, ease of installation, maintenance, measurement accuracy and above all the reliability of the system.

This paper first describes existing BMS topologies together with relevant literature and outlines their benefits and limitations. The proposed classification divides the BMS topologies into

– centralized,
– modularized,
– distributed and
– decentralized.

The identified trend towards the decentralization of BMSs is shown: Centralized BMSs with a single control unit [6–8] are increasingly replaced by a decentralized management, whereby sensor, control and computing resources are distributed [9–13]. The characteristics of the control strategies are therefore analysed and compared.

An approach for a fully decentralized, distributed BMS based on autonomous, locally operating units is proposed. The characteristics and advantages of the proposed approach are described. The requirements, particularly in terms of system control and management, are analysed and challenges to be overcome are identified. The aim is to provide a holistic overview of the features of the proposed BMS and the resulting system requirements.

2 Battery Management System Topologies

2.1 Centralized

In centralized BMSs, the entire functionality is integrated into a single module, which is connected to the batteries or battery cells via several wires (see Fig. 2) [14]. The centralized BMS provides single cell voltage, string current and temperature measurement.

A centralized BMS is described in [15] based on a single chip. The protective function is divided into two stages. The first stage monitors voltage, current, temperature and coordinates the balancing function. Another approach for a centralized BMS is provided in [16]. Advantages of centralized BMS include cost-effectiveness as well as maintenance and repair. If only a single integrated circuit is used, costs are reduced and errors are easily detected. Another advantage is the accuracy, as centralized BMS use the same offsets for all cells. The clearly defined coordination structure provides effective system control.
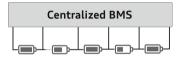

Fig. 2. Reduced block diagram of a BMS based on centralized topology

Disadvantages include the large number of long cable connections, which considerably increase the risk of short circuits. Furthermore, inputs can easily be mixed up and incorrectly connected and connections can become loose, which increases the susceptibility to errors.

Another disadvantage is the lack of scalability and flexibility of the system architecture. In central master-slave BMSs, the maximum number of batteries is strictly predefined. During system development, the number of actively used batteries is fixed and can usually only be changed afterwards by changing the wiring. Adding additional cells is not possible at all if all input connectors are used or vice versa, some inputs might remain unused. In addition, only predefined, mostly single battery technologies are supported and combinations thereof are not feasible.

Furthermore, the master controller is a single point of failure. The entire system control depends on the error-free function of the master controller. In case of failure or malfunction of the master controller, the entire system operation is endangered. This is a significant disadvantage, especially with regard to a reliable, uninterruptible power supply.

2.2 Modularized

Modularized BMSs are characterized by several identical modules, which are connected to the individual batteries or battery cells via cables, similar to centralized BMS (Fig. 3). The BMS modules provide data acquisition (single cell voltage, current, temperature) and communication interfaces to the other BMS modules. Often one of the modules is assigned to the role of master or a separate module serves as master. The master module controls the entire battery pack and communicates with the rest of the system, while the other modules merely record the measured data and transmit it to the master.

A modularized BMS with the aim of improving the performance of BMS to provide a safe, reliable and cost-efficient solution for smart grids and electric vehicles is proposed in [3]. The modularized BMS for electric vehicles presented in [17] focuses on effective single cell monitoring and balancing for a large number of battery cells with comparatively small size and complexity. An advantage of modularized BMSs is the improved manageability. The modules are placed close to the batteries, which avoids long cables. To improve functional safety, the function of the BMS can be easily replicated on the individual modules. The scalability is also increased compared to centralized BMSs. If the battery pack is extended by further cells, another BMS module is simply appended.

The number of inputs of the BMS modules is still fixed and under certain circumstances, inputs may remain unused. In addition, the costs of modularized BMSs are higher. Compared to centralized BMS, the failure of one BMS module does not endanger the entire battery operation. Defective battery cells or batteries are simply removed from the system, reducing capacity but maintaining operation.
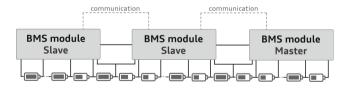

Fig. 3. Block diagram of a BMS based on a modular topology

2.3 Distributed

In distributed BMSs, each cell string or cell is equipped with its own BMS module. The Cell BMS modules provide measurement of operating parameters,

balancing and communication. The BMS controller handles the calculation and communication (Fig. 4).

A distributed BMS divided into a master and several battery modules for real-time monitoring and reporting of battery operating conditions is proposed in [18]. This approach combines central control management and distributed data collection. In order to reduce costs and time-to-market and to increase flexibility, scalability and adaptability, a distributed BMS with smart battery cell monitoring is presented in [19]. The smart battery cell monitoring consists of electronics for monitoring and a data transmission interface for bidirectional communication with the superordinate BMS. The BMS functions as the master and controls energy storage at system level.
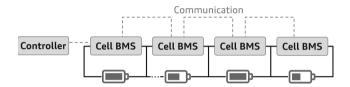
Fig. 4. Block diagram of a BMS based on a distributed topology

The distributed BMS simultaneously offers a high level of reliability and robustness as well as a cost-efficient development process, allowing a significant reduction in the cost of the final battery pack. The advantages of distributed BMSs compared to centralized and modularized topologies are scalability and flexibility. No maximum number of inputs is defined and cells can be added or removed even after installation. This allows easy hardware integration for homogeneous modules. Scaling the battery pack to the size required for different applications does not require any changes to the hardware or software of the modules–only additional battery cell modules have to be assembled or removed. Furthermore, the single point of failure of centralized approaches is avoided. Local control of each cell additionally increases safety. Sensor information only needs to be processed for the local cell and mandatory actions can be triggered immediately. A further advantage is the high measurement accuracy, which is achieved by the specialization of the battery cell module. Furthermore, shorter connecting wires enable more accurate voltage measurement and better interference immunity. Maintenance or replacement of defective parts is facilitated by the modular, distributed architecture.

Disadvantageous are the increased costs for the BMS, as a separate BMS module is required for each cell and for most applications also an additional master module.

2.4   Decentralized

The decentralization of BMSs is a possible solution to overcome the disadvantages of central control structures. Decentralized BMSs consist of several equal

units, which provide the entire functionality locally and autonomously. Each of the individual BMS units is able to operate independently of the remaining ones. Communication lines between the units enable information exchange and task coordination between the units. They are used in several decentralized BMS (Fig. 5). While this architecture offers advantages like scalability, minimal integration effort and increased functional safety, the development requires new methods. Decentralized BMSs are further subdivided into communication-less, wireless and wired communication based topologies. A decentralized BMS without communication requirements is proposed in [20]. The smart cells work locally and autonomously, which increases safety and reliability.

A decentralized BMS based on the droop control for a series connection of battery cells is presented in [21]. Droop control is applied to ensure power sharing among connected components. Droop characteristics are used for the power distribution, which correspond to V-I characteristics in voltage droop control. They determine the required output/input current according to the actual voltage deviation. Physically the droop control behaves like an output resistance. Therefore the droop characteristic is also called virtual resistance. [22,23] Droop control offers high reliability due to the decentralized architecture and the communication-less control. A drawback of the droop-based control is the imprecise control [24]. With the consideration of line resistance in a droop-controlled system, the output voltage of each converter cannot be exactly the same. Therefore, the output current sharing accuracy is affected. In addition, the voltage deviation increases with the load due to the droop characteristic [25].

Due to the possibility of cable breaks in wired communication systems like CAN or I^{2}C, BMS approaches based on wireless communication are developed [26]. As a possible solution, [26] proposes a distributed and decentralized wireless BMS based on an Internet of Things (IoT) network.

In [27], a fully decentralized BMS is proposed, whereby the entire BMS functionality is integrated into the cell management units. One cell management unit per cell is used, providing local sensing and management capabilities autonomously and system-level functionality by coordination via communication. A CAN bus is used for wired communication, which enables broadcast communication between the cells. The major advantage of decentralized BMSs is the absence of a central control unit, on which error-free function the entire operation depends. Furthermore, the scalability and flexibility are advantageous. The number of inputs is not fixed and can be extended/reduced even after installation.
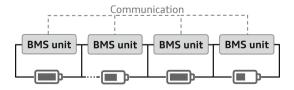

Fig. 5. Block diagram of a decentralized BMS

A challenging feature is the distributed system control based on the equal, parallel-operating and autonomous nodes. In addition, it has to be ensured that the single point of failure is not only shifted but eliminated. For a reliable system, a holistic approach is required.

2.5 Overview and Evaluation of the Battery Management System Topologies

The decentralization of the BMS topology results in functionality distributed to several individual units. The functional units are closer to the battery/battery cell and more elaborately equipped to work independently. Operation is becoming increasingly independent of a central coordination unit and the failure of individual functional units has a minor impact on the system function. As a result, the reliability of the system is improved. The scalability increases with rising decentralisation. The number of batteries/battery cells is not limited by pre-defined inputs but is variable even after the initial layout. Individual batteries/battery cells can be added or removed. A variable number of batteries results in enhanced flexibility. The BMS is adaptable to the requirements of a wide range of applications.

Table 1 summarizes the evaluation of existing BMS topologies in terms of reliability, scalability and flexibility. Compliance with the criteria is evaluated, where $++$ means full compliance, $+$ partial compliance, 0 neutral, – partially not satisfied, and – – not satisfied at all.

Table 1. Evaluation of existing BMS topologies in terms of reliability, scalability and flexibility

BMS topology	Reliability	Scalability	Flexibility
Centralized	– –	– –	– –
Modularized	0	–	–
Distributed	+	+	+
Decentralized	++	++	++

3 Decentralized Battery Management System Based on Self-Organizing Nodes

The proposed system is fully decentralized and consists, in contrary to the proposed approaches, of three types of modules: renewable energy producers, batteries and consumers. All components are connected together with a common power line and at least one global communication bus (Fig. 6).
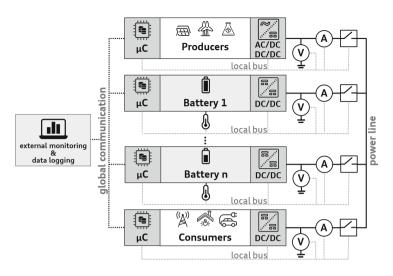
Fig. 6. Block diagram of the decentralized BMS

3.1   Distributed Control

For distributed, autonomous control, each battery, producer and consumer is equipped with its own local control unit (LCU). The LCU includes:

– Current, voltage and temperature measurement to record actual operating parameters,
– a communication interface for data exchange between the components.
– a microcontroller for calculation, data management and evaluation,
– a DC/DC converter with target current and target voltage values which are adjustable during operation, and
– a relay which is opened in case of failures to avoid safety critical voltage levels or for maintenance purposes.

Producers and consumers use the LCU to provide their operating parameters for load/generation forecasts and for voltage control. Batteries provide the ability to absorb excess power or deliver missing power and thus are able to control the system. Therefore, additional algorithms for system control and leader election are implemented on the LCUs of the batteries.

The implemented software for system control manages both the actual operating data such as current, voltage and temperature and the system states resulting from previous measurements. The SOC and the SOH are determined. In addition, the battery fitness (BF) is defined. The BF is a numerical value based primarily on SOC, SOH, number of charge cycles, time of last charge/discharge, the system-wide normalized capacity and the actual operating parameters. Taking into account the optimum operating range of the respective battery technology, the battery condition is evaluated. The criteria, e.g. SOC or temperature, are weighted. The criteria weighting can be adjusted depending on the battery

technology and the system status. The adjustment of the weighting provides the basis for system optimization according to various criteria such as cost minimization, maximum safety or availability. The BF enables a system-wide definite evaluation of different battery technologies. In turn, this enables the combination of different battery technologies in a single system. The combination of different battery technologies offers advantages including optimization of the system control, extending battery life and increasing system reliability [28]. Additionally, it offers a second life application to a wide range of batteries [29,30].

The BF is also a decision criterion for the leader election. The participating nodes work autonomously and locally and control the system in a collaborative manner. Highly parallel computer systems exist for solving complicated mathematical problems. In contrast, the challenging task in the context of the proposed approach is to structure, intelligently equip and network the nodes to such an extent that the overall system and its control interact harmoniously. The LCUs are interacting in the physical domain in their control task while communication latency for negotiations is high compared to the control requirements. In addition, in reality the nodes do not work perfectly synchronized but asynchronously [31]. Therefore, the development of a system control consisting of decentralized, autonomous, distributed, asynchronous nodes is a non-trivial, challenging task. The target of the decentralized control structure is to make the system independent of the error-free function of a component. This can be achieved if the role of the central control unit is not permanently assigned to a single component.

Therefore, instead of the decentralized system control being distributed to all nodes, the approach of the system control coordinated by a temporary master which gets reassigned on a regular basis was chosen. One LCU of the batteries is chosen as the temporary central control unit applying a leader election algorithm. The temporary central control unit determines the required charge/discharge power of the remaining battery nodes, taking into account their BF. In case of failure, malfunction or changes in control capability, one of the battery nodes is selected as the new central control unit. As a result, the single point of failure of existing centralised approaches is avoided.

3.2   Communication

Communication between the peer nodes is the key to the autonomous, local control of the decentralized BMS. For autonomous decision making and system control, the nodes communicate their operating parameters and work on a system-wide consistent database. A suitable communication methodology is required to enable fast and energy-efficient communication between the nodes. Furthermore, a robust communication architecture is required to withstand the harsh environments of e.g. automotive applications. In addition, establishing a secure communication protocol between the individual nodes is essential for the safe operation of the BMS. Therefore a well-proven, robust, noise-free, fast and reliable communication technology is required. To achieve a minimum of integration effort, an architecture with minimal wiring harness is required for the distributed topology.

A bus-based communication architecture achieves higher bandwidth and enables broadcast communication between the nodes, which is advantageous for the leader election and system control. Controller Area Network (CAN) is a robust bus-based broadcast communication technology. It is particularly suitable for applications with a small amount of information to be exchanged. Furthermore, CAN is a message-based network and each node is equipped with a filtering mechanism that filters messages based on their identifiers. Thus, only messages relevant to the node are considered. Due to its characteristics CAN is chosen as communication technology for the decentralized BMS. For first implementations a communication based on a single CAN bus is used. For future developments dual CAN, CAN in combination with optical data transmission via polymer optical fiber (POF) and CAN combined with Ethernet are conceivable approaches providing diverse redundancy to increase system reliability and availability.

3.3   Suitability for Active Balancing

The decentralized BMS is able to support active balancing. On the one hand, weaker batteries are protected by taking the BF and thus also the SOC into account when setting the target value for individual energy delivery. In addition, batteries with higher SOC are set to higher target currents during discharge while those with lower SOC absorb higher charging currents. On the other hand, the controllable relays allow individual batteries to be disconnected from the power line. An additional power line between the batteries could additionally enable effective, active balancing by connecting the batteries to be balanced (Fig. 7). This architecture enables one-to-one, one-to-many and many-to-many balancing at a voltage level controlled by the DC/DC converter [32]. Taking into account the BF, the system–wide standardised nominal capacity and the SOC, the more powerful batteries supply the weaker ones.

3.4   Scalability and Integration

The number of inputs and thus of participants is not fixed in the proposed decentralized BMS. A minimum of two batteries is recommended for a reliable supply. Adding and removing nodes is possible after installation and during operation. Both hardware and software are designed for effective integration [33]. The variable number of participants, which can be adjusted and changed during operation, allows the system to be adapted to requirements changing over its lifetime. Optimizations in terms of e.g. cost efficiency, safety or maximum service life can be implemented or changed. The reconfigurable architecture increases reliability, performance and flexibility of the proposed BMS [34].

3.5   Flexibility

The variable number of participants and the possibility to use and combine different battery technologies increases the flexibility of the system. Existing
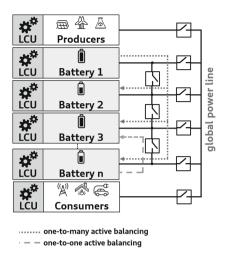
Fig. 7. Additional lines and individually controllable relays enable one-to-one, one-to-many and many-to-many active balancing

approaches tend to specialize in a single battery technology [35,36]. In order to improve the performance and energy density, new battery technologies are constantly being developed [37–39]. The BMS is flexible and effective in adapting to changing conditions for optimal and safe battery operation. The software is effectively expandable and software updates during operation support the effective integration and potentially necessary software adjustments supporting new battery technologies [40].

3.6   Fields of Application

The flexible, scalable, reconfigurable architecture opens up various fields of application including uninterruptible power supply, electric vehicles, (islanded) dc microgrids, grid support for peak load shaving or load management. The applications result in different requirements for the BMS. For electric vehicles, for instance, high availability, safety and energy density with minimum size and weight are required. For islanded micro grids, the relevant criteria include effective service lifetime, cost efficiency, reliability and resistance to environmental effects. In addition, various battery technologies and combinations thereof are supported. The combination of different battery technologies improves the system control as well as the battery life of various applications [41]. Furthermore, second life and second use applications are possible for a large number of batteries [30].

4   Conclusion

In this paper, existing BMS topologies were presented and discussed in terms of scalability, flexibility and reliability (cf. Table 1). A decentralized, distributed

BMS based on self-organized and locally operating nodes was proposed. The system control is distributed among the LCUs, which record operating parameters and provide their own computing and communication capacities. Possible approaches for the coordination of a control system based on a many-microcomputer system were suggested. Communication requirements were analysed and suitable technologies were selected. The resulting flexible architecture allows optimized system configurations for a wide range of applications, adaptability to newly developed battery technologies and multi-criteria optimizations.

5   Outlook

Future developments will further optimize the reliability and fault tolerance of the system. Several communication technologies are combined to achieve various redundancies. As a fallback strategy in case of communication failure, the implementation of a droop-based control is planed. It is avoided to move only the single point of failure. The goal is to avoid a single point of failure holistically on the system. Additionally a strategy for active charge balancing during operation under consideration of the BF, which does not require additional hardware, will be developed.

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