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A Review of Management Architectures and Balancing Strategies in Smart Batteries

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Abstract—**Battery management systems (BMSs) play a critical role to ensure the safety and extend the lifetime of the Lithium-ion batteries. In the conventional BMSs, there are some disadvantages such as low scalability and insufficient flexibility. In order to enhance these performances and further increase their reliability, the smart batteries are proposed. The smart batteries are the cell-level BMSs, which are built by the integrated cell modules connected in series. Each integrated cell module can monitor its own states, control the bypass circuit, and can communicate with the master controller, thus they are also called smart cells. This paper presents the state-of-the-art of management architectures, communication implementations, bypass circuits, and bypass decision strategies in the smart batteries. Four different existing smart batteries are compared. According to the comparison, future trends of the smart batteries are provided.**

Keywords—Smart battery, battery management system, management architecture, communication, balancing strategy, bypass circuit

I. INTRODUCTION

Lithium-ion batteries have been widely used in many different applications, such as electric vehicles (EVs), energy storage equipment, cell phones and laptops due to their high energy density, long lifetime, and high efficiency [1]. Battery management systems (BMSs) are necessary for these devices in order to guarantee the safe operation and extend the lifetime of the battery pack. The main tasks of BMSs are monitoring and balancing cells in the pack. A simple solution to balance battery cells is energy dissipation, which generally consumes the excess energy by connecting a shunting resistor in parallel with each cell. This approach is also called cell-to-heat balancing method or passive balancing method due to its low efficiency. In order to reduce the energy losses, various energy transfer balancing topologies are proposed, which transfer the energy from the high energy cells to the low energy cells, thus this approach is called active balancing method. According to the energy transfer routes, energy transfer topologies are divided into five types: adjacent cell-to-cell (AC2C), direct cell-to-cell (DC2C), cell-to-pack (C2P), pack-to-cell (P2C), and cell-to-pack-to-cell (C2P2C) [2]-[3]. The energy of the battery pack is not wasted, and the efficiency is significantly increased. Modularized architecture is the practical management configuration in these conventional BMSs, as shown in Fig. 1. In the modularized architecture, several cells are connected in series to form a battery module and are monitored by a battery module sensor. All module sensors collect the voltage and current information of the cells and send the information to the master controller,

then the master controller sends the equalizing commands to the balancing circuit according to the present states of each cell [4]. Low cost due to only one controller is the advantage of this architecture. However, the faulty tolerance is very low: once a cell is broken, the entire system cannot work properly. In addition, the design is complex and needs isolated networks between the master controller and the battery modules [2].
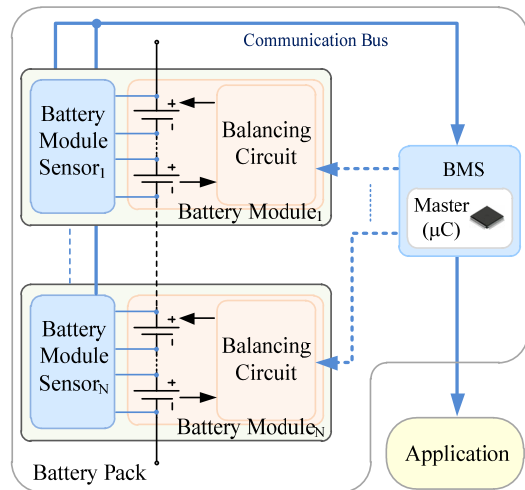

Fig. 1. Conventional modularized battery management architecture.

The smart batteries are seen as the future trend for BMSs due to their high reliability, scalability, and flexibility. These battery systems are built by connecting the smart cells, which are the integrated cell modules. Each smart cell has its own controller that integrates voltage and current sensors, ambience or temperature monitors, communication devices, and the bypass circuit. In addition, the cell controller can estimate the state-of-charge (SOC) and the state-of-health (SOH) as well as predict the remaining useful lifetime (RUL) of the smart battery. Another advantage of smart batteries over conventional BMSs is high modularity, which easily allows to extend the battery capacity by adding more smart cells, and to replace bad cells due to no direct connection among cells.

This paper presents the state-of-the-art of smart batteries, and also provides the future trends for the smart batteries. Section II reviews the management architectures and the communication implementations for smart batteries. Section III presents the balancing circuits and the decision strategies for smart cells. Section IV compares four existing smart batteries. The future trends of smart batteries are presented in Section V.

II. MANAGEMENT ARCHITECTURES AND COMMUNICATIONS

This section presents centralized management architectures and distributed management architectures for smart batteries as well as their advantages and challenges. In addition, various methods of wired communication and wireless communication are provided.

A. Centralized Management Architecture

In a centralized management architecture, each cell is connected to a bypass circuit, which is managed by a slave controller. As shown in Fig. 2, the battery cell, the bypass circuit, and the slave controller are the three primary elements of a smart cell. All cells are connected in series through the bypass device in order to form the battery pack. At the system level, a master controller is used for sending the commands of power, current, and voltage requirements to the slave controllers. In some balancing algorithms, the master controller also collects voltage or SOC data of each cell from the slave controllers, and then makes the bypass decision and send the commands to slave controllers [5]. The slave controllers collect the information of the cells, including the measurement of voltage, current, and temperature, and send the bypass/insert signal to the bypass device according to the commands from the master controller. If the balancing method is based on SOC and SOH, the slave controllers also estimate SOC and SOH of the battery cells. There is no requirement of additional communication between cells due to the master-slave control mode. In order to improve the faulty tolerance of the smart battery, there will be some redundant cells connected in series. This approach will also expand the capacity of the battery pack.
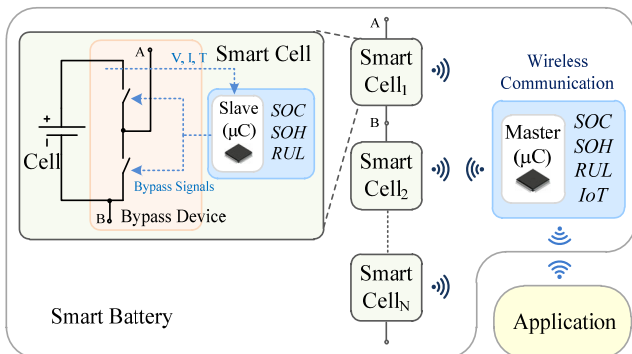

Fig. 2. Centralized management architecture for smart batteries based on wireless communication.

B. Distributed Management Architecture

A distributed management architecture is proposed in [6]. This architecture is also built by the smart cells connected in series, and the composition of each smart cell are the same as in the centralized architecture. The difference between the centralized architecture and the distributed architecture is no master controller in the later one. A completely distributed system is provided in [7]. The proposed system is to use Modular Multilevel Converter (MMC) in low-power system. The distributed architecture is not applied in most smart batteries, because the cells need to know the system information, such as the bus voltage and the average cell voltage or SOC, and based on this, decide the working mode. A fully distributed photovoltaic (PV) inverter architecture is provided in [8]. There

are four-stage controllers: maximum power point tracking (MPPT) stage, dc voltage control stage, current/power control stage, and modulation control stage. All stage controllers are operated using a decentralized control strategy. In [9], a fully decentralized power balance control for grid-connected cascaded modular inverters is provided. In this control method, each module can make decisions to realize accurate power balance without any communication. This method is expected to be used in PV and storage cascaded systems. The distributed control method in other applications may give some inspiration to smart batteries.

C. Advantages and Challenges of Management Architectures in Smart Batteries

Compared with the conventional management architectures, the management architectures of smart batteries have the following advantages:

- High modularity and scalability. The smart cells can connect in series to expand the capacity without changing the system configuration.

- Good flexibility. The battery cells can come from different manufacturers and can have different capacities. The balancing circuit adapts the status of the cells to the battery pack.

- High reliability. Each smart cell works independently. If one or several cells are empty or broken, the system will bypass the cells and continue working. But in the conventional architecture, once a cell is broken, the battery pack cannot work due to direct connection among cells.

- Easy installation. Less wires are required due to no need of communication wires and the additional balancing devices among cells.

However, there still have some challenges in smart batteries:

- Cost. Each cell in the smart battery requires a controller and a bypass device. This results in a considerable increase of components. But with the development of the integrated chips, the cost is expected to significantly drop.

- Efficiency. The efficiency of several experimental prototypes can achieve to 90%-93%. In a similar module-integrated system of PV applications, the efficiency can achieve to above 98% [10], the efficiency of the smart batteries thus can be increased.

- Voltage drop of the battery pack. The smart cells work in the bypass mode. With more cells bypassed, the dc bus voltage will decrease. For EV applications or energy storage systems, the dc bus voltage range is large enough, thus it is no need to consider this problem. But the number of bypassed cells should be controlled within a reasonable range.

D. Wired Communication

The communication reliability is very important for BMSs due to the requirement of exchanging information and cooperation between the master controller and the slave

controllers. Most of the existing BMSs adopt centralized or modularized architectures with the standard bus system [11]. In [12], a hierarchical active balancing architecture is proposed. It is operated in master-slave control mode based on CAN bus communication. In [1], it adopts a centralized smart battery architecture with I²C bus. In [13], the authors propose a BMS architecture based on an isolated power/data multiplexing transmission bus, which is also operated in master-slave control mode. The power/data bus uses a common bus to transfer energy between cells and send the data and commands between the master controller and slave controllers; therefore, the system wiring is simplified. However, wired-communication systems have some disadvantages: (1) large and complex wiring increases the cost, weight, and size of the battery pack [14]; (2) limited scalability and flexibility due to the fixed wiring; (3) manufacturing difficulty [15]-[16].

E. Wireless Communication

With the rapid development of wireless communication technology, some researchers consider to use this technology in order to enhance the performance of the BMSs. A wireless battery management system (WBMS) is presented in [15] to improve several issues of the conventional BMSs. The WBMS uses wireless communication technology and combines the characteristics of smart batteries to manage the battery system. The Internet of Things (IoT) component is the most important element for WBMS. It consists of an IoT system-on-chip and a communication device, such as Sub-GHz, Wi-Fi, or ZigBee. In [11], the various antenna types and the different frequency ranges for wireless channels of a battery pack are evaluated and measured. In [17], the author proposed the operating process between local cell sensors and system control units via the wireless communication. An integrated Sub-GHz sensor node with the remote power-up receiver is presented in [18]. It is suitable for densely distributed wireless sensor network and can cover the radius of sensor network over three meters. In [19], an application with Wi-Fi technology is proposed. In this application, the master controller is a Zedboard with an additional Wi-Fi module, and the slave controller is CC3220SF Simplelink Wi-Fi wireless microcontroller unit (MCU). The communication between the master controller and the slave controllers is via Wi-Fi signal transmission. Fig.2 shows the idea of the Wi-Fi feedback in smart batteries. It verified that the Wi-Fi technology is a possible communication solution in smart batteries. Linear Technology and BMW cooperated to produce the first industry wireless automotive BMS concept car. This illustrates that the WBMS in EVs is entirely possible and prospect [20]. In [16], IoT gateway can work with cloud support network. This means the IoT can receive the information about the cell status, the control demands, and even the optimized algorithms on board from the cloud server (i.e., google cloud).

III. Balancing Strategies

Smart batteries transfer more energy to the low energy cells during the charging period, and consume more energy from the cells with high energy during the discharging period, so the balancing method of smart batteries is the active balancing method due to its low loss. The balancing strategy is bypassing cells based on the voltage or SOC of the battery cells. In the smart batteries, each cell has an isolated bypass device, as shown

in Fig. 3. The power can flow in both direction during the charging period and the discharging period. Currently, there are dc/dc converter bypass strategy and direct bypass strategy in the smart batteries. In the following, two balancing decision strategies and different bypass circuits are introduced.
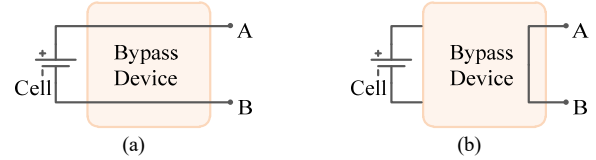

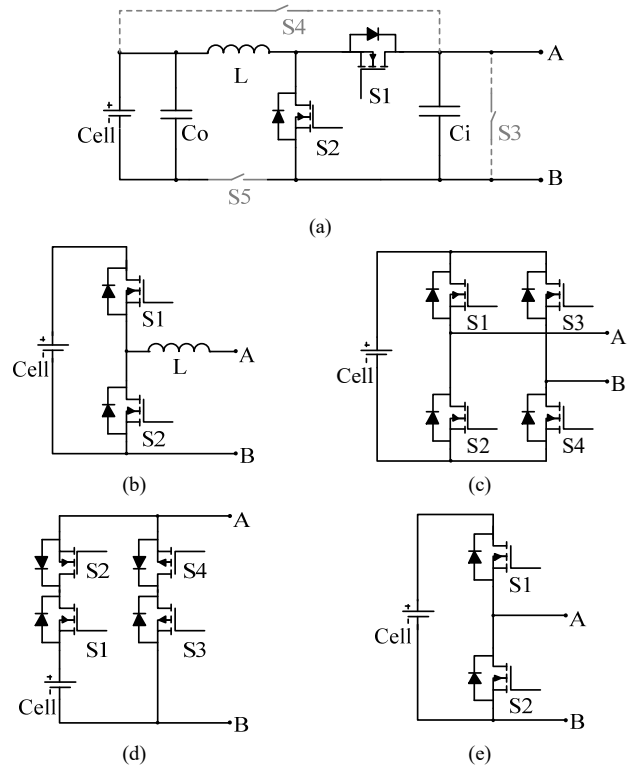Fig. 3. Bypass function of the smart cell: (a) cell insert; (b) cell bypass.

Fig. 4. Various bypass circuits of the smart cells: (a) enhanced synchronous bidirectional converter; (b) half-bridge converter with a filter inductor; (c) full-bridge converter. (d) four switches bypass circuit; (e) half-bridge bypass circuit.

A. DC/DC Converter Bypass Strategy

For the dc/dc converter bypass strategy, the dc/dc converter works periodically, and the bypass time should synchronize with the average voltage or SOC of all battery cells. In [1], an enhanced synchronous bidirectional converter is proposed. This converter uses two switches to realize the cells balancing and adds additional three switches to reduce the bypass and insert loss, as shown in Fig. 4(a). Each cell compares its voltage to the average voltage of all cells in the battery pack. If the voltage is higher/lower than the average voltage, the duty ratio of S1 will decrease/increase, respectively. The synchronous bidirectional converter can boost the voltage of the dc bus side, so it can use less cells to achieve the same bus voltage. The disadvantage of this converter is the use of five switches for each cell, which increases the switches loss and the system cost. The half-bridge converter with a filter inductor used in the smart battery is

presented in [7]. The function of the filter inductor L, as shown in Fig. 4(b), is to minimize the output voltage ripple for each cell. The voltage through the inductor contains the useful information of each cell. According to these information, the smart cells can decide the switching mode and the duty cycle for two switches in order to adjust the average SOC of all battery cells. Because the distributed inductors are small enough, the size of the smart cell doesn't increase. A full-bridge converter used in the smart batteries is presented in [21], as shown in Fig. 4(c). This converter enables the entire battery pack to work in ac and dc condition, and it is suitable for energy storage devices. In addition, it verified the balancing system with redundant cells obtain more capacity than the balancing system without redundant cells both in ac and dc conditions. The authors of [21] also proposed a hierarchical distributed balancing system based on full-bridge converter in [22]. The hierarchical system has three layers, module, bank, and system respectively, and it is suitable for large-scale ac battery packs.

B. Direct Bypass Strategy

The direct bypass strategy bypasses cells at any time according to the voltage or SOC [23]. Fig.5 shows the balancing process of three cells via bypassing the lowest SOC cell directly during the discharging period. The bypass period provides the cells a rest time to finish the internal electrochemical reaction and reduce the stress on cells, the lifetime therefore can be increased. In [24], the cycle life test verified that the rest period can extend the life cycle of cells with over 20%. In addition, the open circuit voltage (OCV) can be measured at the end of the rest time, which can be further used for a rough battery SOC estimation.
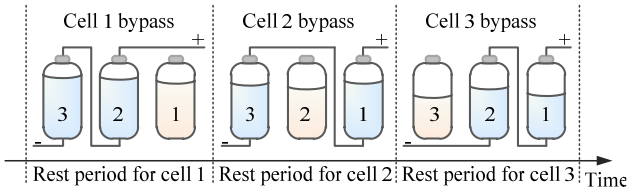

Fig. 5. The balancing process of direct bypass strategy during discharging period.

A four switches bypass circuit is presented in [23], as shown in Fig. 4(d). Two N-channel MOSFETs (NMOSs) S1 and S2 connect with the cell in series and work in the inserting period. The other two P-channel MOSFETs (PMOSs) S3 and S4 connect the cell in parallel and work in the bypassing period. This bypass system has one more redundant cell and can balance cells based on the voltage or SOC of each cell. In normal operating mode, n-1 cells are connected by NMOSs; and one cell is bypassed by PMOSs. The authors considered using custom IC integrating the switches in this bypass system, so the one redundant cell method is suitable for light EVs due to the limited technique. For the high power loads, the modularized structure should be considered and there will be several redundant cells. A half-bridge circuit used in the bypass system is proposed in [5], as shown in Fig. 4(e). The control strategy is bypassing several cells to balance a large battery pack based on the SOC of cells. There are less components in half-bridge topology, which can improve the efficiency and loss, and also reduce the size and cost of the entire battery system.

C. Decision Strategy

Two balancing decision strategies have been used in the smart batteries: voltage-based and SOC-based. Voltage-based balancing decision strategy requires the terminal voltage of each cell, so the controller only needs to monitor the voltage of each cell. Voltage-based balancing criterion is easy to realize. However, the terminal voltage includes the OCV, and voltage drops due to ohmic and polarization resistance, so it cannot reflect the real SOC of the cells. In addition, there are certain Lithium-ion battery chemistries, which have a flat voltage characteristic as is the case of Lithium Iron Phosphate (LFP) batteries. The SOC range of the flat voltage is about 20%-90% [25]. If the batteries are used in hybrid electric vehicles (HEVs), which generally work in this range, the voltage variation is less than 0.1V and therefore hardly to balance cells well. SOC-based balancing decision strategy can solve the problems mentioned above. This method needs more status information of all cells, including the accurate measurement of current and voltage. The SOC estimation has to be also performed in the slave controller. The easiest SOC estimation method is Coulomb Counting method, which is based on the integration of current. There are many more accurate SOC estimation methods, but only few of them are suitable for embedded systems [26]. However, this will not be a problem if the IoT can be applied to the smart batteries in the future. Additionally, SOH can be a part of the decision strategy based on IoT technology [27].

IV. COMPARISON

The existing smart batteries can be divided into four categories. The comparison of various smart batteries are presented in Table I. The following conclusion can be drawn from the table:

- The number of components in the direct bypass circuits is less than that in dc/dc converters, because the direct bypass topologies only need power switches.

- The direct bypass balancing system has higher efficiency, because the main loss in the system is the conduction loss of the power switches. In addition, the direct bypass circuits are operated in low switching frequency mode, so the switching losses are lower than that in the dc/dc converter In [5], the bypass device is a half-bridge circuit, which only has two switches for each cell and the overall switching frequency is 0.1Hz. Low loss is an advantage of this direct bypass system as the efficiency can be above 97%.

- The dc/dc converters are based on the voltage balancing strategy, while the direct bypass topologies are commonly based on the SOC balancing strategy. The terminal voltage cannot directly reflect the SOC of cells, therefore the SOC-based decision strategy is the better criterion to control the balancing process or minimize the differences of SOCs among cells.

- The dc/dc converter are usually applied in energy storage systems. The direct bypass balancing methods are used in EVs.

- The complexity of the direct bypass system is lower than of the dc/dc converter. In the direct bypass system, the

circuits are built by the switching matrix. In the dc/dc converter, some special components need to be designed, such as the filter inductor in [7]. This increases the design and control complexity of the system. In addition, the flexibility decreases due to the customized components.

- Compared with conventional architectures of BMSs, the scalability of smart batteries increases significantly, because the power and the capacity can be scaled up by adding more smart cells to the system. Comparing these four smart systems, the distributed one shows a high scalability due to no communication requirements between battery cells as well as the slaves and the master. However, this system is only suitable for low-level control system, so the scalability is still limited. The smart battery based on wireless communication shows an excellent scalable performance due to no fixed wiring for communication in the system.

- The wireless communication can improve the reliability of the BMSs. It can address the potential physical failure of connectors, cables and harnesses in some difficult conditions, such as the high vibration environments for EVs.

- The direct bypass period provides the rest time for cells to complete chemical reactions, thus the lifetime of battery cells and the entire battery pack can be extended. The dc/dc converters are operated in high-frequency mode, so the bypass time is too short to be an effective rest period for cells.

- Compared with the conventional BMSs, the system cost increase due to the large number of controllers. However, wireless communication technology applied in the smart batteries can reduce the wiring cost, and the simple half-bridge circuit with less components also can save the cost. Therefore, the forth system presents the cost advantage.

TABLE I.   COMPARISON OF THE EXISTING SMART BATTERIES

Comparison criteria	Centralized dc/dc converter balancing system based on wired communication [1]	Distributed dc/dc converter balancing system based on wired communication [7]	Centralized direct bypass balancing system based on wired communication [23]	Centralized direct bypass balancing system based on wireless communication [5] [19]
Number of power switches per cell	Five	Two	Four	Two
Switching frequency	250kHz	20kHz	-	0.1Hz
Efficiency	93%	-	>90%	>97%
Decision strategy	Voltage-based	Voltage-based	Voltage-based or SOC-based	SOC-based
Application	Energy storage system; second use battery system	Energy storage system; low power application	Light EVs (electric scooters and bikes)	EVs; large battery pack
Complexity	++[a]	++	+++	+++
Flexibility	++	++	+++	+++
Scalability	+	++	+	+++
Reliability	++	++	++	+++
Life extension	++	++	+++	+++
Cost	+	+	+	++

[a.] +: good; ++: very good; +++: excellent.

V. FUTURE TRENDS OF SMART BATTERIES

The smart battery is a promising research area for BMSs. There are several future trends for smart batteries:

- Wireless communication. Low cost can be achieved by wireless technologies due to the reduction of communication components such as the wiring harnesses and connectors. This also reduce the complexity of design and productivity. In addition, the flexibility and reliability will increase significantly as no requirements of fixed communication wiring [15].

- Direct bypass balancing strategy. Unlike in dc/dc converter balancing circuits, direct bypass circuits only need few switches to bypass or insert cells. The advantages of the direct bypass are high efficiency, easy control, low switching frequency, less components, and low cost [5].

- SOC and SOH decision strategy. Compared with the voltage decision strategy, the SOC can reflect better states of cells and is thus more suitable for direct bypass circuits. In recent years, many researchers have contributed to SOC estimation and achieved certain results. Moreover, it is expected that SOH will be a part of the decision strategy and combines with SOC together to determine the states of cells and also realize cells balancing [7].

- Rest period control. The rest time allows recovery time for the cells, which can reduce the stress on cells. Rest period combined with direct bypass balancing strategy can extend the battery capacity and increase the battery lifetime [24].

- The pulse frequency technique for quick charging [28]-[29]. The pulse frequency technology reduces the charging time for batteries with low temperature rising about 1 °C and thus increase the battery lifetime.

- Distributed architecture. With the development of wireless communication technologies, cells can communicate with each other without being restricted by communication wires. The master controller will be removed, and the reliability and flexibility of the battery system will increase [16].

- Reconfigurable battery management architectures. Reconfigurable techniques can control arbitrary the number of cells to be connected in series or parallel, thus has the ability to increase or decrease the voltage or capacity of the battery pack [30]. The reconfigurable battery system can improve the efficiency, lifetime, safety, and reliability of the battery packs [31].

REFERENCES

[1] Y. Li and Y. Han, "A Module-Integrated Distributed Battery Energy Storage and Management System," *IEEE Trans. Power Electron.*, vol. 31, no. 12, pp. 8260–8270, 2016.

[2] M. M. Hoque, M. A. Hannan, A. Mohamed, and A. Ayob, "Battery charge equalization controller in electric vehicle applications : A review," *Renew. Sustain. Energy Rev.*, vol. 75, no. November 2015, pp. 1363–1385, 2017.

[3] S. Yang, Y. Cui, J. Zou, Y. Chen, and X. Liu, "A Multi-winding Transformer Cell-to-Cell Active Equalization Method for Lithium-Ion Batteries with Reduced Number of Driving Circuits," *IEEE Trans. Power Electron.*, vol. 31, no. 7, pp. 1–1, 2015.

[4] C. H. Kim, M. Y. Kim, and G. W. Moon, "A modularized charge equalizer using a battery monitoring ic for series-connected li-ion battery strings in electric vehicles," *IEEE Trans. Power Electron.*, vol. 28, no. 8, pp. 3779–3787, 2013.

[5] B. Majmunovic, R. Sarda, R. Teodorescu, C. Lascu, and M. Ricco, "Highly efficient smart battery pack for EV drivetrains," *2017 IEEE Veh. Power Propuls. Conf. VPPC 2017 - Proc.*, vol. 2018–Janua, pp. 1–5, 2018.

[6] S. Steinhorst, M. Lukasiewycz, S. Narayanaswamy, M. Kauer, and S. Chakraborty, "Smart Cells for Embedded Battery Management," *2014 IEEE Int. Conf. Cyber-Physical Syst. Networks, Appl.*, pp. 59–64, 2014.

[7] D. F. Frost and D. A. Howey, "Completely Decentralized Active Balancing Battery Management System," *IEEE Trans. Power Electron.*, vol. 33, no. 1, pp. 729–738, 2018.

[8] H. Jafarian, "Hybrid Current- / Voltage-Mode Control Scheme for Distributed AC-Stacked PV Inverter With Low-Bandwidth Communication Requirements," *IEEE Trans. Ind. Electron.*, vol. 65, no. 1, pp. 321–330, 2018.

[9] X. Hou *et al.*, "A Fully Decentralized Control of Grid-Connected Cascaded Inverters," vol. 10, no. 1, pp. 2018–2020, 2019.

[10] R. C. N. Pilawa-Podgurski and D. J. Perreault, "Submodule integrated distributed maximum power point tracking for solar photovoltaic applications," *IEEE Trans. Power Electron.*, vol. 28, no. 6, pp. 2957–2967, 2013.

[11] D. Alonso, O. Opalko, M. Sigle, and K. Dostert, "Towards a wireless battery management system: Evaluation of antennas and radio channel measurements inside a battery emulator," *IEEE Veh. Technol. Conf.*, pp. 1–5, 2014.

[12] Z. Zhang, H. Gui, D. J. Gu, Y. Yang, and X. Ren, "A hierarchical active balancing architecture for lithium-ion batteries," *IEEE Trans. Power Electron.*, vol. 32, no. 4, pp. 2757–2768, 2017.

[13] R. Zhang, J. Wu, R. Wang, R. Yan, Y. Zhu, and X. He, "A Novel Battery Management System Architecture based on an Isolated Power/Data Multiplexing Transmission Bus," *IEEE Trans. Ind. Electron.*, vol. PP, no. c, p. 1, 2018.

[14] D. an Alonso, O. Opalko, and K. Dostert, "Channel Measurements and Simulations with Planar Inverted F-Antennas in an Enhanced Testbed for a Wireless Battery Management System," pp. 1–8, 2015.

[15] A. Chon, I. Lee, J. Lee, and M. Lee, "Wireless Battery Management System (WiBMS) Outline," *Adv. Automot. Batter. Conf. Eur. 2016*, pp. 1–5, 2016.

[16] T. Faika, T. Kim, and M. Khan, "An Internet of Things (IoT)-Based Network for Dispersed and Decentralized Wireless Battery Management Systems," *2018 IEEE Transp. Electrif. Conf. Expo, ITEC 2018*, pp. 342–346, 2018.

[17] V. Roscher *et al.*, "Synchronisation using wireless trigger-broadcast for impedance spectroscopy of battery cells," *SAS 2015 - 2015 IEEE Sensors Appl. Symp. Proc.*, pp. 1–6, 2015.

[18] J. Lee, I. Lee, J. Park, J. Moon, S. Kim, and J. Lee, "A sub-GHz low-power wireless sensor node with remote power-up receiver," *Dig. Pap. - IEEE Radio Freq. Integr. Circuits Symp.*, pp. 79–82, 2013.

[19] J. L. Lafrenz *et al.*, "Application Layer Design for Smart Battery Pack Control with Wi-Fi® Feedback," *2018 IEEE Energy Convers. Congr. Expo. ECCE 2018*, no. c, pp. 5586–5590, 2018.

[20] W. Bms, "Wireless Battery Management Systems Highlight Industry ' s Drive for Higher Reliability."

[21] E. Chatzinikolaou and D. J. Rogers, "Performance Evaluation of Duty Cycle Balancing in Power Electronics Enhanced Battery Packs Compared to Conventional Energy Redistribution Balancing," *IEEE Trans. Power Electron.*, vol. 33, no. 11, pp. 9142–9153, 2018.

[22] E. Chatzinikolaou and D. J. Rogers, "Hierarchical Distributed Balancing Control for Large-Scale Reconfigurable AC Battery Packs," *IEEE Trans. Power Electron.*, vol. 33, no. 7, pp. 5592–5602, 2018.

[23] A. Manenti, A. Abba, A. Merati, S. M. Savaresi, A. Geraci, and S. Member, "A New BMS Architecture Based on Cell Redundancy," *IEEE Trans. Ind. Electron.*, vol. 58, no. 9, pp. 4314–4322, 2011.

[24] B. Lawson, "A Software Configurable Battery," 2012.

[25] R. Xiong and W. Shen, *Advanced Battery Management Technologies for Electric Vehicles*. Wiley, 2018.

[26] M. A. Hannan, M. S. H. Lipu, A. Hussain, and A. Mohamed, "A review of lithium-ion battery state of charge estimation and management system in electric vehicle applications : Challenges and recommendations," *Renew. Sustain. Energy Rev.*, vol. 78, no. May, pp. 834–854, 2017.

[27] T. Gherman, "Smart Integrated Charger with Wireless BMS for EVs," *IECON 2018 - 44th Annu. Conf. IEEE Ind. Electron. Soc.*, vol. 1, pp. 2151–2156, 2018.

[28] C. Praisuwannl and S. Khomfoi, "Pulse Frequency Technique for a Quick Charger," 2013.

[29] C. Praisuwanna, "A Quick Charger Station for EVs Using a Pulse Frequency Technique," *2013 IEEE Energy Convers. Congr. Expo.*, pp. 3595–3599, 2013.

[30] S. Steinhorst *et al.*, "Distributed Reconfigurable Battery System Management Architectures," *2016 21st Asia South Pacific Des. Autom. Conf.*, pp. 429–434, 2016.

[31] S. Ci, N. Lin, and D. Wu, "Reconfigurable Battery Techniques and Systems: A Survey," *IEEE Access*, vol. 4, pp. 1175–1189, 2016.