Electric Vehicle Enhanced Range, Lifetime And Safety Through INGenious battery management

D6.1 – Analysis of the state of the art on BMS

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EXECUTIVE SUMMARY

To protect individual battery cells and the entire battery pack from exothermic reactions, an electronic safety circuitry is required [1]. For this purpose, the term battery management system (BMS) has emerged. The most important task of the BMS is to fulfil safety functions in such a way that the cells in a battery system are not operated beyond their specified limits in terms of voltage, temperature and current. Generally, a BMS is an analogue and/or digital electronic device [1], expected to achieve the following key objectives and requirements [2], which are essential for automotive applications:

- Increase safety and reliability of battery systems.
- Protect individual cells and battery systems from damage.
- Improve battery energy usage efficiency (i.e., increased driving range).
- Prolong battery lifetime.

The individual functions of a BMS can then be derived from these requirements [1]. According to [3], these functions can be categorized into five areas: Sensing and high-voltage control, Protection, Interfacing, Performance management and Diagnostics.

The different possibilities to connect several individual cells in a battery pack lead to different possible configurations and architectural designs of a BMS. Also, the different tasks fulfilled by a BMS can be distributed among different subcomponents – typically, printed circuit boards – of a BMS configuration [4].

In a centralized BMS, up to three tiers – cell monitoring unit, module management unit and pack management unit [5] – are combined into one single printed circuit board, which handles all the tasks required from the BMS and is directly connected to the battery cells. In a modular BMS topology, the module management unit is divided into multiple, separate instances, which can be placed close to the battery modules, thus reducing the wiring complexity. A further advanced variant of the modular topology is the master-slave-topology. Here, the functions and elements of the slaves are reduced to a minimum and functions that relate to the complete battery system are implemented only on the master.

Within this study, 40 commercial BMS of 29 different manufacturers were analyzed. 37 out of the 39 BMS variants – of which the location could be identified – are from manufacturers located either in Western Europe, North America, Japan or China. Only one in the group is located in Australia and the remaining one in South Korea.

It has been found that 18 of these products exhibit centralized topologies, while 22 have a modular one. Furthermore, 20 of the 22 modular BMS that have been considered in the analysis are intended to manage battery packs for battery electric vehicles, while 13 out of 18 centralized systems are specified to be only suitable for applications of 200 volts and below.

Although some of these centralized BMS allow to be interconnected establishing a larger-distributed topology, high-voltage applications are more likely to be addressed by modular BMS, partly because it is more challenging to handle insulation in a centralized system compared to several subsystems with lower voltage levels [6]. An exception is the 360 V system of the Nissan Leaf [7]. However, a disadvantage of modular systems is the large number of communication and power supply circuits needed and the resulting, comparably higher costs [8].

The analysis shows only seven BMS from the total which are not explicitly intended to operate in BEVs. Consequently, they do not work with high voltage levels. Five out of this group of seven show a centralized structure.

The costs overhead is even higher for distributed systems with multiple instances of centralized boards, as there are inevitably redundant components on the boards [9]. This is possibly the reason why this topology has been found to be not so widespread in this study. In a distributed BMS

topology, there exist several stand-alone pack management units that supervise their own set of cells or supercells.

Almost every considered BMS in the study uses at least one CAN-bus communication line. The reason for this wide-spread use of the CAN-bus might be the easy interfacing to other controllers in the automotive environment, which often use CAN communication [10]. Wireless BMS layouts, which replace the internal communication between the modules with wireless network, can have potential advantages including reduced cable harnesses, connectors and wiring effort during assembly. However, a challenge of wireless BMS is the possible disturbance of the wireless network by electro-magnetic noise from within the car [11] and outside entities, which may create safety and security issues.

During the development of a BMS, there are various aspects to be considered to assure the safe operation of the battery system. In the last decades, safety standards have emerged for the development of hardware and software parts of electrical and electronic systems.

In this study, the application of the ISO 26262 standard "Road vehicles – Functional Safety", a derivation of the general industry standard IEC 61508, is considered for BMS development [12], [13].

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List of Abbreviations and Acronyms

ACRONYM	DEFINITION
AFE	Analog Front-End
AGV	All Green Vehicles
ANN	Artificial Neural Network
APEJ	Asia Pacific Excluding Japan
ASIC	Application Specific Integrated Circuit
ASIL	Automotive Safety Integrity Level
B2B	Business to Business
BCU	Battery Control Unit
BDU	Battery Disconnect Unit
BEV	Battery Electric Vehicle
BMM	Battery Management Module
BMS	Battery Management System
BMU	Battery Monitoring Unit
BP	Back Propagation
CAN	Controller Area Network
CB	Cell Board
CC	Constant Current
CCS	CAN Current Sensor
CCU	Central Controller Unit
CM	Controlling Module
CMU	Cell Monitoring/ Management Unit
CP	Constant Power
CPC	Cooperative Patent Classification code
CSC	Cell Supervision/Sensor Circuit
DIN	Deutsches Institut für Normung
DOD	Depth of Discharge
DOW	Description of Work
E/E	Electrical and Electronic
EIS	Electrochemical Impedance Spectroscopy
EOL	End of Life
ESC	External short Circuit
ETA	Event Tree Analysis
EV	Electric Vehicle
EVI	Electric Vehicle Initiative
EVPST	Electric Vehicle Power System Technology Co.
FIT	Failure in Time
FMEA	Failure Mode and Effect Analysis
FMEDA	Failure Mode Effects and Diagnostic Analysis
FRC	Failure Rate Class
FTA	Failure Tree Analysis

HIL	Hardware in the Loop
HSI	Hardware and Software Interface
HV	High Voltage
IC	Integrated Circuit
ICEV	Internal Combustion Engine Vehicle
ISC	Internal Short Circuit
LFM	Latent Fault Metric
LIFePO4	Lithium Iron Phosphate
LV	Low Voltage
mA	milliamp
MCU	Module Control Unit
MM	Managing Module
MMU	Module Management Unit
NCA	Nickel Cobalt Aluminum Oxide
NIMH	Nickel Metal Hydride
NMC	Nickel Manganese Cobalt
OCV	Open Circuit Voltage
OEM	Original Equipment Manufacturer
PCB	Printed Circuit Board
PCU	Power Controlling Unit
PHEV	Plug-in Hybrid Electric Vehicle
PMB	Power Measurement Board
PMU	Pack Monitoring Unit
PQL	Prototype Quality Level
RTOS	Real Time Operating System
RUL	Remaining Useful Life
SEooC	Safety Element out of Context
SIL	Software in the Loop
SIM	System Interface Module
SM	Sensing Module/ Safety Mechanism
SOA	Safe Operation Area
SOC	State of Charge
SOF	State of Function
SOH	State of Health
SOL	State of Life
SPFM	Single-Point Fault Metric
SSE	Surpass Sun Electric Co. Ltd.
STW	Sensor Technik Wiedemann
TM	Testing Module
WiBMS	Navitas Solutions Wireless Battery Management System
WP	Work Package
WPL	Work Package Leader

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INTRODUCTION

The term Battery Management System (BMS) does neither have a universal or formal definition [1], [2], nor does exist a unique summary with the tasks it should perform. The main reason is the strong dependence of its features and capabilities on the application: e.g. automotive, aerospace, stationary storage systems or consumer electronics applications, etc [14]. There is no ideal solution for all the needs of battery management which derives from the diverse choices in terms of battery chemistry or geometry [15]. Sporadically, it can be found that terms such as "voltage management systems" or "protection circuit module" are employed when referring to them [1].

In general, it is understood that a BMS is a system responsible for the supervision, control, and protection of battery cells – either individually or connected to form battery packs – and these are, in consequence, fundamental tasks for many aspects of the electrified vehicle performance; from energy efficiency – and therefore range – to safety, battery life and reliability [16].

But of course: for the sake of a formal definition a common understanding does not suffice.

SETTING THE BMS IN A CONTEXT

The sustained improvement occurred during the last decade, in terms of the energy density and costs, has made the lithium-ion cell the energy source of choice for electric vehicles (EV). According to the Global Electric Vehicle Outlook 2016 [17], the energy density of battery packs for Plug-In Hybrid Electric Vehicles (PHEV) has improved from 60 Wh/L in 2008 up to 295 Wh/L in 2015, attaining with this an outstanding 400% improvement. On the other hand, figures show that specific costs have fallen from USD 1000/kWh down to USD 268/kWh in the very same lapse of time, representing a remarkable reduction of 78%.

In some specific cases, Original Equipment Manufacturers (OEM) have announced better achievements for 2015 in terms of costs and energy densities. General Motors, for example, has declared that the battery costs for its Chevrolet Bolt fell down to USD 145/kWh in October 2015 and a reduction below the USD 100/kWh is expected by 2022 [18]. Another renowned Battery Electric Vehicle (BEV) manufacturer – Tesla – is aiming to break the USD 100/kWh barrier by 2020 as well [19]. Realistic targets such as USD 125/kWh, 400 Wh/L and 250 Wh/kg for xEVs have been already set for 2022 [17], [20], which will allow the achievement of cost competitiveness towards conventional Internal Combustion Engines Vehicles (ICEV) and the announcement of driving ranges never heard before.

But even though the lithium-ion technology has magnificently performed during the last decade, mainly due to its good energy and power densities, it is neither a mature technology, nor a safe one in every possible operating condition. Lithium-ion chemistry is very susceptible to over temperatures, overvoltage, deep discharge and overcurrent, conditions which may and have recently damaged batteries in real life applications [21]–[26]. And not only the number and type of hazards derived from this technology is what demands for the implementation of complex, safety management tasks, but also the current and advantageous trend of development in terms of energy density: the bigger the amount of packed energy per volume unit, the higher the intensity of the hazard.

With the development of the FP7 research projects STALLION und STABALID, thermal runaway was confirmed as the main safety hazard in lithium-ion batteries [27]. This undesirable phenomenon is often caused under abuse conditions which can be thermal – overheating; electrical – deep discharge and high rate charge, especially at low temperatures; high pulse power; or mechanical – crushing, which can eventually turn into internal or external short circuits (ISC, ESC). In addition to its susceptibility to the operation under extreme conditions, the lithium-ion technology has shown other issues which must be taken into account for its effective and safe utilization in an energy storage system. The most significant are summarized and briefly commented below.

For supplying the EV drivetrain with the required levels of voltage and current, many lithium-ion cells must be connected in series [2], [5] and, in some cases, many in parallel. This conditions directly the resultant energy storage capacity, the weight and, approximately, the range the vehicle will be able to drive from a single charge. Of course, the demand of connecting several cells in series cause the immediate need for the implementation and control of high voltage safety measures – for their normal operation, as well as for maintenance activities. Furthermore, the number of connections will have a direct impact on the characteristics of the BMS architecture to be employed, regarding both – hardware and software. In addition to that, the geometry and dimensions of the cells within the battery pack will have an influence too.

Cells with lithium-ion technology show, regardless of their use, capacity fading and an increase in internal resistance over their lifetime [28]. This phenomenon is referred to as ageing and can occur due to cycling in a normal operation regime or due to storing the cells and not using them; the so-called calendar ageing. In either case, the temperature of the surrounding medium influences the aging processes; or the temperature gradient across the entire volume of the battery pack, when in use, lead to inhomogeneous ageing of the lithium-ion cells over their lifetime. Inhomogeneous aging creates further problems.

The spread in the ageing characteristics during normal operation of series connected lithium-ion cells, as well as differences in their self-discharging rates, lead to charge unbalances [2], [29], [30]. The unbalance reduces the usable total capacity of the battery pack, either because the least charged cell determines the end of discharge – even if there is still usable energy stored in the other cells – or because the most charged cell determines the end of the charging process. Ignoring these two extreme conditions would eventually lead to deep discharge or overcharge, which might favor the occurrence of the aforementioned thermal runaway phenomenon. What's more, the inefficient use of the battery capacity will cause a more frequent cycling, shortening that way the battery life. Therefore the need of equalizing the charge across the serial connected cells in the battery pack arises.

BMS RELATED RESEARCH TOPICS

The mitigation of the issues above mentioned are fundamental reasons for permanent research activities. The literature reports developments in the field of cell modelling which allows the effective monitoring of cells and battery packs [28], [31], [32]. Cell monitoring focuses mainly on the accurate determination of the internal states of a cell; namely the State of Charge (SoC) as the primary indicator of the actual energy content of the battery pack and charge unbalances; the State of Health (SoH), either based on the cell's capacity or internal resistance, which indicates ageing; or the State of Function (SoF), which describes how the battery's performance can meet the application's demand while in use; e.g. power demand, cranking capability or charge acceptance, etc. Furthermore, research activities on the subjects of cells balancing [29], [30] and its impact on the battery life [33], [34] are found to be equally relevant in the scientific literature.

While so much effort is currently being paid to the mitigation of the aforementioned issues in lithium-ion cells, safety itself is the research topic of paramount importance. Considerable amounts of resources are being dedicated to achieve a proper understanding and a consistent experimental reproduction, description – or modelling – of phenomena such as thermal runaway, cell plating, lithium dendrites development, current collector dissolution and gas evolution [35], as well as the influence of the environmental and operational conditions on them. The aim is turning the current state-of-the-art reactive safety management into a model based one, with the ability to provide relevant information on safety issues and possible hazards well in advance – hours and even days – meanwhile guaranteeing the vehicle's driver a doable scenario where to achieve a safe state [27]. Of course, the traditional sensing strategies – cells currents, voltages and external temperatures – are not going to be neglected in the future. Moreover, novel sensing strategies involving cell acoustic and strain information, together with sensorless internal temperature estimations, like those based on the execution of Electrochemical Impedance Spectroscopy (EIS) experiments [36], will be considered.

But safety comprises not only the analysis and the implementation of algorithms, sensing strategies and counter measures such as states estimation, high voltage, electric or thermal management, in order to prevent the energy storage system from hazardous events, mainly linked to phenomena that intrinsically belong to the electrochemistry. The development, implementation and execution of the abovementioned activities in an on-board setup, namely the automotive BMS, imply putting into practice a set of more basic, but still technologically complex tasks, in order to assure the proper utilization of the energy storage system. Among them are acquisition, processing, storage and data communication, as well as the control of dedicated sensors and actuators, such as pole cutting relays, pre-charge and interlock circuits, insulation monitoring devices and the like [2], [14].

A FEW WORDS ON FUNCTIONAL SAFETY AND SECURITY

When considering the context in which an automotive BMS is expected to operate, the tasks it needs to perform and the necessary infrastructure in hardware and software which will accomplish all that, it can be promptly understood that a practical design and implementation of an automotive lithium-ion energy storage system imply, additionally, different kind of risks and failures; from the design and development phases, going through its serial and large implementation by the automotive industry, and finalizing later on with its decommissioning and disposal. Properly handling such a complex system during its entire life cycle can only be effectively achieved by employing the related standards and the existence of the proper – quality and safety – management apparatus.

Several are the standards associated to the lithium-ion energy storage systems and, in general, to the electro mobility. The automotive industry is putting them into practice nowadays. Of great significance for the lithium-ion energy storage systems and its BMS are the so-called ISO 26262 standards – a derivation for the satisfaction of the automotive industry of the IEC 61508. Both commit to the safety life cycle of electric and electronic products. The ISO 26262, together with the ISO 9001, allows and regulates the instrumentation of an efficient Safety Management System. Due to its importance, research is also carried out on the application of the ISO 26262 to the life cycle of the lithium-ion energy storage systems for the automotive industry and the BMS [37], [38].

Finally, IT security issues have recently shown up in the industrial and automotive embedded control systems scenarios. Examples of those cyberattacks can be found in [39], [40], while more and more security flaws in the embedded control systems of cars and other road vehicles are discovered [41]. Today the average new car has more lines of software code than those in the Hubble Space Telescope, a Boeing 787 Dreamliner, and all the source code on the Facebook app combined [42]. And with cars becoming no less than mobile data centers – capable of supporting a variety of new protocols – considering IT security on the development of those systems became already obliged. The malicious manipulation of the data the BMS receives or the corruption of the BMS control systems could unavoidably have catastrophic consequences from a safety point of view.

ORGANIZATION OF THE DOCUMENT

Having briefly exposed the context in which the current analysis of the state of the art on BMS architectures is going to be carried out, the proposed organization in sections of this document is presented next.

Section "1. BMS overview, classification and analysis" will expose in detail the existent topologies in hardware, whether modular or centralized, which can be identified in the publically available literature, as well as their characteristics, tasks, advantages and disadvantages. The significant characteristics of the BMS provided by the third party BMS manufacturers identified in section 4, when available, are going to be employed within this first section, aiming to support the theoretical aspects here covered.

Section "2. Functional safety processes for automotive BMS design" will introduce the standardization results that are of relevance to the e-mobility Battery Management Systems, in the sense of functional safety. Of special interest within this section are going to be the characteristics of the ISO 26262 standard, and the approaches found in the literature for its application to the automotive BMS.

Section "3. Intellectual property on cell monitoring algorithms" will delve into the theoretical fundaments for the implementation of the cell monitoring strategies presented in patents, which have been assigned to the relevant payers identified in section 4.

Section "4. An overview of the e-mobility BMS market" will address relevant automotive BMS manufacturers and suppliers which operate all over the world and, where possible, those acting within the supply chain of the relevant OEMs. Where relevant to the analysis, other third party – non-automotive – BMS manufacturers will be considered as well as their products. Their relevant research, development and standardization activities are going to be commented, from the information provided by news and press releases at their own information channels.

In sections 5, general conclusions drawn from the analysis of the state of the art on BMS as well as recommendations for further activities are going to be stated.

In section 6, the relevant metadata of the employed information sources, consulted for this analysis of the state of the art on BMS architectures, will be listed.

Following, additional and relevant information to the study will be allocated in annexes.

1 BMS Overview, Classification and Analysis

1.1 BMS Functionality and Design

Starting at the battery cell level and moving up to the battery system level, this section gives an overview of the basic functions of a battery management system (BMS). The definition of different topologies enables a categorization of BMS.

1.1.1 From Battery Cells to Battery Packs

In contrast to a gasoline or diesel tank in a combustion-engine car, lithium-ion accumulators contain both an oxidizer (cathode) and a fuel (anode) closely together in a sealed container. Under normal conditions, the fuel and oxidizer convert the chemical energy to electrical energy in a controlled way and with minimal heat and gas development. However, in the case of failure or if the cell is operated outside the specified limits (in terms of temperature, voltage, and current), the reaction can quickly become uncontrolled and exothermic. This can lead to a so-called thermal runaway, which is an irreversible process where more heat is released than can be dissipated from the cell housing. This process can lead to fire and explosion and put the environment at significant risk [43]–[45].

Basically, there are three different build types for lithium-ion accumulators: so-called pouch-bag cells, round cells, and prismatic hard-case cells [2]. For the manufacturing of the cells, different cell chemistries, materials and additives are used. These factors influence the behavior of the cell outside of its specification limits [46]. The closer lithium-ion accumulators are operated near their specification limits, the more their ageing processes are accelerated and the lifetime of the cells is being reduced.

The specification limits of individual cells are differing in this context. For example, the end-of-charge voltage differs with respect to the used anode and cathode materials. For many lithium-ion and lithium-polymer accumulators, an end-of-discharge voltage of 2,5 V and an end-of-charge voltage of 4,2 V is determined by the cell chemistry [12], [47]. In comparison, for graphite/lithium iron phosphate ($LiFePO_4$), the end-of-charge voltage is only 3,7 V [48]. The specification limits for charge and temperature in addition differ for various cell types and cell chemistries and depend on the cell production process, mainly in the case of high power and high energy cells [46]. The current load of a cell depends on the used additives, separators, the cobalt content of the cathode, and the current conductors in the cell [46].

Depending on the application, individual cells are used or several cells are connected in series or parallel in a module. Quite common is the connection of 8-12 cells in series [2]. To increase the capacity, either several individual cells can be connected in parallel to form a so-called supercell, or several modules can be connected in parallel. This is referred to as a battery system or battery pack [12]. Thus, through series connections, the voltage level of the battery pack can be defined, while through parallel connections, its capacity can be defined. In a battery pack, the connections can either be purely in series, purely in parallel, or a mixture of series and parallel connections can be present. In this way, the voltage level and the capacity can be adapted to the specific requirements of the application, for instance hybrid electric vehicle (HEV), battery electric vehicle (BEV) or stationary storage applications [2], [12],[49].

The international norm ISO 6469-3 defines the high voltage range as 60V – 1500 V for direct-current voltage, and 30 V – 1000 V for alternating-current voltage (so-called voltage class B). To carry out work in this high voltage range, specific training and certificates are necessary. Therefore, battery modules are typically designed in such a way that the total voltage of a module is less than 60 V and thus in voltage class A [2]. This enables to handle modules without cost-intensive safety measures during production and transport.

Overall, the battery can thus be considered as a hierarchical structure consisting of three layers [1], [50]:

- Cell (basic element; about 3V to 4V in the case of lithium-ion battery chemistries)
- Module (collection of series-connected cells, in a dedicated physical case; up to 60V)
- Pack (connection of modules, arranged in series and/or parallel; up to 1000V)

1.1.2 BMS Requirements and Functions

To protect individual battery cells and the entire battery pack from the aforementioned exothermic reactions, an electronic safety circuitry is required [1]. For this purpose, the term battery management system (BMS) has emerged. The most important task of the BMS is to fulfil safety functions in such a way that the cells in a battery system are not operated beyond their specified limits in terms of voltage, temperature, and current. This set of specification limits for cells is often referred to as its safe operation area (SOA).

Generally, a BMS is an analogue and/or digital electronic device [1] that fulfils the following essential requirements [2], [14]:

- Data acquisition.
- Data processing and data storage.
- Electrical management.
- Temperature management.
- Safety management.
- Communication.

For electric vehicles, according to [2] the following key objective and requirements are essential for a BMS:

- Increase safety and reliability of battery systems.
- Protect individual cells and battery systems from damage.
- Improve battery energy usage efficiency (i.e., increased driving range).
- Prolong battery lifetime.

The first two requirements refer to safety, whereas the last two requirements refer to comfort.

The individual functions of a BMS can then be derived from these requirements [1]. According to [3], these functions can be categorized into five areas as follows:

1. Sensing and high-voltage control: The BMS must measure cell voltages, module temperatures, and battery-pack current. It must also detect isolation faults and control the contactors and the thermal-management system.
2. Protection: The BMS must include electronics and logic to protect the operator of the battery-powered system and the battery pack itself against over-charge, over-discharge, over-current, cell short circuits, and extreme temperatures.
3. Interfacing: The BMS must communicate regularly with the application that the battery pack powers, reporting available energy and power and other indicators of battery-pack status. Further, it must record unusual error or abuse events in permanent memory for technician diagnostics via occasional on-demand download.
4. Performance management: The BMS must be able to estimate state-of-charge (SOC) for all the cells of the battery pack, compute battery-pack available energy and power limits, and balance (equalize) cells in the battery pack.
5. Diagnostics: Finally, the BMS must be able to estimate state-of-health (SOH), including detecting abuse, and may be required to estimate the remaining useful lifetime of the battery cells and pack.

This list includes safety-relevant functions, like for instance the sensing of the cell voltages, but also comfort functions, like for instance the estimation of the state-of-charge (SOC). Independent of the aforementioned requirements and functions, the system has to be tested for electrical safety and must comply with the necessary measures.

1.1.3 BMS Subcomponents and Topologies

Based on the principles discussed above, the different possibilities to connect several individual cells lead to different possible configurations and architectural designs of a BMS. Also, the different tasks fulfilled by a BMS can be distributed among different subcomponents - typically, printed circuit boards (PCBs) - of a BMS configuration [4]. Brandl et al. [5] proposes a classification of the subcomponents of a BMS into three tiers:

- Cell monitoring unit (CMU): Lowest level, one unit attached to each cell. The CMU measures cell voltage, temperature, and additional parameters on cell level and provides cell-level balancing.
- Module management unit (MMU): Middle level, manages and controls a group of CMUs and therefore cells (usually between 8 and 12 cells). The MMU groups them into a module and provides inter-cell balancing functions.
- Pack management unit (PMU): Highest level, manages and controls MMU. The PMU communicates with external systems, measures pack-wide parameters such as pack current and voltage, and controls pack safety devices.

As noted in [5], the terms CMU, MMU and PMU are not standardized, and there are sometimes other terms used in the literature and in the automotive industry. For instance, "central management unit" is also used as a term for the PMU, or "data acquisition unit" for the CMU, or "cell supervisor circuit" for the MMU with integrated CMU.

Using this classification of the tiers, the following three principled variants of BMS topologies can be distinguished.

Centralized BMS

In a centralized BMS, all three tiers (CMU, MMU, PMU) are combined into one single entity (printed circuit board, PCB), which handles all the tasks required from the BMS and is directly connected to the battery cells. This topology is schematically depicted in Figure 1.1.

Centralized BMS are simple and compact, but difficult to scale. One reason is that with an increasing number of cells, the wiring of the cells to the BMS becomes complex. Also, isolation requirements become difficult to meet for high-voltage packs, as the voltage drop at the BMS inputs is equal to the total voltage of the battery pack in this arrangement.

The centralized BMS topology is therefore generally feasible for accumulators with a small number of cells only, and not commonly employed for electric vehicles with larger battery packs. A noteable exception is the BMS for the Nissan Leaf. However, centralized BMS are often used, for example, in small low-capacity electric bicycles with only a limited number of cells.

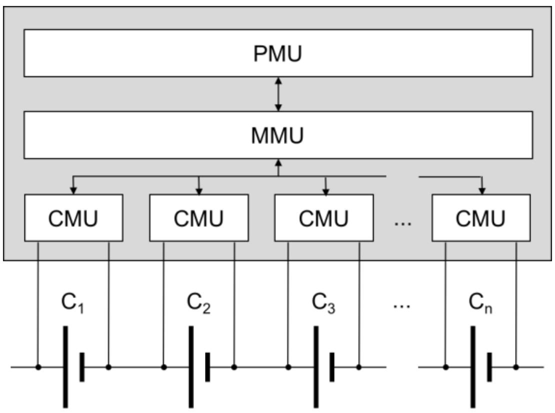


Figure 1.1: Centralized BMS topology [2].

Modular and Master-Slave BMS

In a modular BMS topology, the MMU is divided into multiple, separate instances. These can be placed close to the battery modules, thus reducing the wiring complexity. The MMUs then transfer the cell parameter measurements to the PMU via a communication interface. This internal communication can be accomplished, for instance, via CAN bus or isoSPI [44]. Thus, in contrast to the centralized BMS topology, in a modular arrangement the PMU is connected only indirectly with the individual cells.

A further advanced variant of the modular topology is the master-slave-topology. Here, the functions and elements of the slaves, also called cell supervision circuits (CSC), are reduced to a minimum and functions that relate to the complete battery system are implemented only on the master. Therefore, with this topology the cost of the slave modules are further reduced [1].

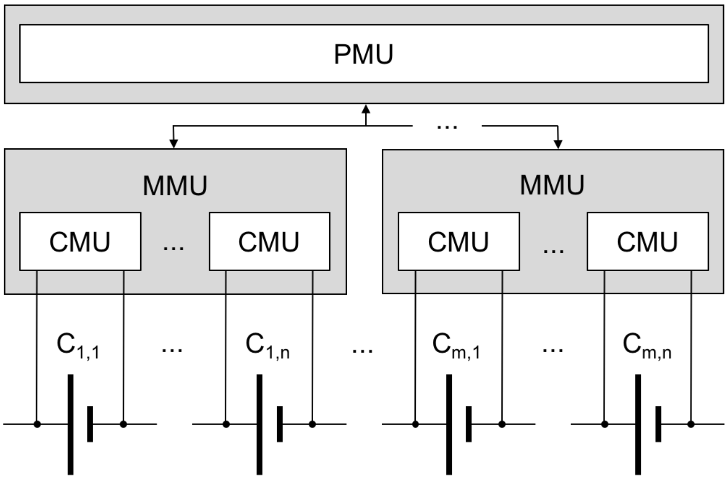


Figure 1.2. Modular BMS topology [2].

Distributed BMS

In a distributed BMS topology, there exist several stand-alone PMUs that supervise their own set of cells or supercells. The different PMUs can communicate with each other and, depending on the requirements, either work autonomously or receive and issue control commands from other PMUs. The most far-reaching variant is the so-called smart battery cell concept, where each battery cell is equipped with its own dedicated microcontroller.

This topology offers maximum flexibility and scalability, but has also the highest complexity and costs, since a complete arrangement of CMU, MMU, and PMU is required for each set of cells or supercells.

The different topologies are compared in [1] with respect to measurement quality, immunity to noise, versatility, safety, ease of installation, and cost. Centralized BMSs are economical, but least flexible and scaleable. Distributed BMSs topologies are the most expensive and versatile, and simplest to install. Modular and master-slave BMSs topologies offer a good compromise of the advantages and disadvantages of the other two topologies.

1.1.4 Components of a High-Voltage Battery Pack

In addition to the functions of the BMS, a comparison and analysis of BMS also requires basic knowledge of the structure of a high-voltage (HV) battery pack. Therefore, in this section, the typical components of a battery pack are briefly presented and the relationships are shown schematically.

Starting with the requirements placed on a battery pack and its application, special components can be required. Basically, in the case of a battery electric vehicle (BEV), it consists of battery modules, a BMS, a cooling system, a battery disconnect unit (BDU) [51], the housing, and interfaces for the

HV and data connections. These components are schematically shown in Figure 1.3, where the BDU is called "switch box" (sometimes the BDU or switch box is also called “battery junction box”).

On each battery module, a BMS slave is located in this case, which performs the direct cell monitoring and is connected to the BMS master. The BDU contains – apart from the the HV contactors, which switch the battery pack voltage to the outside – a fuse, a total voltage and total current sensor, a precharge resistor, and an isometer. The precharge resistor limits the inrush current and the isometer checks whether the housing or the vehicle mass are sufficiently isolated from the high-voltage parts. The BMS may also actively manage the temperature of the pack by controlling a heater to keep its minimum operating temperature, or a fan or liquid cooling system to keep it below its maximum operating temperature.

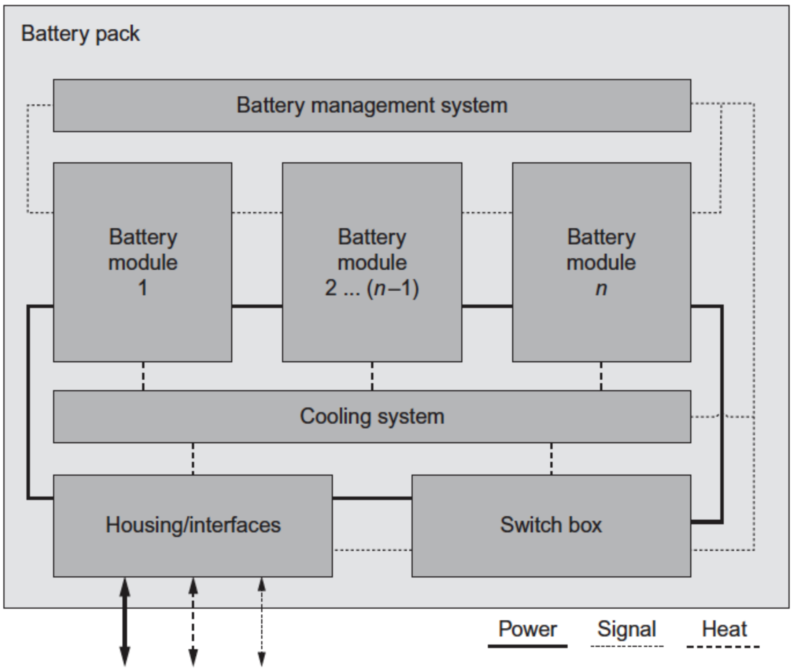


Figure 1.3. Schematic depiction of the main components of a high-voltage battery pack [2].

1.1.5 BMS Integrated Circuits (ICs)

The BMS uses integrated circuits (ICs, also referred to as microchips) to implement its functions. This section provides an overview of ICs that are available today for BMS design. ICs used in BMS can be divided into battery sensor ICs that provide measurements of the cell voltages and temperatures, and microcontroller ICs that make use of the sensor values in order to determine the state of the battery pack and protect the cells from operating outside safe operating regions.

In addition, ICs for battery management can be distinguished into generic ICs, and purpose-designed ASICs (application-specific integrated circuits). In addition, in some more research-oriented and experimental BMS designs - for example, Fraunhofer’s FoxBMS or Altera’s BMS reference design - it has been suggested to incorporate so-called FPGAs (field programmable gate arrays). FPGAs are ICs that can be configured by a customer or developer after manufacturing. They can be used to accelerate computationally intensive tasks in the BMS, such as Kalman-filtering for parameter identification of battery cells, and support the main microcontroller.

A detailed, although not fully up-to-date outdated discussion of BMS circuit design can be found in [1].

Battery Monitoring ICs

Several ICs for measuring cell parameters (voltage, temperature, and current) are available that differ with respect to measurement accuracy, power consumption, footprint, and cost.

Common manufacturers of cell-monitoring ICs for battery management applications include:

- Linear Technology: Linear Technology's LTC6802, LTC6803 and LTC6804 line (http://www.linear.com/products/Multicell_Battery_Stack_Monitor) can handle multiple cell chemistries and measure cell voltages from 0V to 5V for up to 12 cells. It is designed specifically for HEV traction packs.
- Intersil: Intersil's ISL78610 and ISL78600 line (http://www.intersil.com/en/products/end-market-specific/automotive-ics/cell-balancing-and-safety/ISL78610.html) is designed specifically for automotive applications and can monitor up to 12 Li-ion cells.
- Maxim: Maxim's MAX14920, MAX14921 line can handle 3-16 Li-ion cells. (https://www.maximintegrated.com/en/products/power/battery-management.html)
- Texas Instruments: Texas Instruments is the de-facto leader in ICs used in small Li-ion batteries, such as cell phones and laptops.
- Analog Devices: Analog Devices's AD7280 Lithium Ion Monitoring IC is similar to the Linear Technology chip.

Instead of monitoring all their attached cells in parallel, the cell sensor ICs often incorporate a so-called multiplexing architecture that switches the voltage from each cell (input pairs of wires) in turn to a single analogue or digital output line. This approach reduces costs, but it incurs the drawback that only one cell voltage can be monitored at a time, potentially loosing important information due to sampling. A high-speed switching mechanism is then required to switch the output line to each cell so that all cells can be monitored sequentially in sufficient frequency.

Battery Main-Controller ICs

Common chip architectures used for microcontrollers in battery management systems include:

- ARM Cortex: Cortex M0, Cortex M1, and Cortex M4 are a family of processor cores for use in embedded microcontrollers. The Cortex-M4 core includes optionally a floating-point unit. Manufactures include e.g. Atmel, Microchip, STMMicroelectronics, NXP, Texas Instruments, and Infineon.
- MIPS 4K: MIPS is a modular microcontroller architecture for embedded systems that supports optional co-processors and floating-point units. There is a wide availability of embedded development tools for MIPS. Examples include e.g. the PIC32-processor family by Microchip.
- TriCore: Tricore is a dual-core, 32-bit microcontroller architecture from Infineon. It is specifically designed for use in automotive and safety-critical applications.
- 68000: The 68000 is a 32-bit microprocessor architecture originally developed by Motorola. Manufacturers include Texas Instruments, Siemens, and NXP.

1.1.6 BMS Computing and Software Architecture

The decision to distribute BMS functions applies across different units, or to concentrate it into a single unit, not only applies to hardware parts. The software and the associated processing power needed for the BMS functions can also be structured in different ways.

In the centralized BMS topology, which uses only a single microprocessor, this unit is responsible to implement all software functions in a single software application.

In a modular or master-slave architecture, however, each slave device will typically have a microprocessor responsible for, at least, voltage and temperature measurement as well as cell balancing. While it is possible to implement additional functionality in these microcontrollers, there are certain limitations, as for example slave modules may not always have access to all system inputs [15].

Similar as for other embedded control systems, BMS implementations often follow a multi-tier architecture. This means that the BMS software functions can be divided into different layers [15]:

- Low-level layer for device drivers and hardware interface routines.
- Middle layers providing implementations of communications protocols and interpretations of physical measurements.
- Upper layers for high-level battery computations such as state-of-charge and power limit calculations.
- Top-level applications layer responsible for decision making based on information provided by lower levels.

The strict use of such a multi-tier approach and its abstraction layers maximizes the re-usability and maintainability of software code for the BMS. For example, an application that decides to connect or disconnect the battery based upon its SOC does not need information about how the SOC is being calculated, and in fact it may be advantageous to use different methods of SOC in different applications. Consequently, there is no need for the SOC calculation algorithm to understand the details of how its inputs (temperature, voltage, current) are processed. More generally, if the layered architecture is maintained, any of the layers can be modified with limited consequences to adjacent layers [15].

Most BMS software architectures implement a multi-tasking environment for the different functions of the BMS. This environment can range from simple round-robin task schedulers to more complex, fully preemptive multi-tasking operating systems [15]. As the BMS is a safety-critical system, it is necessary to ensure that tasks responsible for safety functions – such as voltage measurement and the associated overcharge and over-discharge protection, temperature and current measurement, and contactor actuation – are performed in a timely fashion to ensure prompt responses to potential hazards. In a pre-emptive multi-tasking environment where it is possible that tasks are temporarily interrupted to perform others and then resumed later, it is of vital importance that safety-critical BMS tasks will not be significantly delayed and performed too late. In order to ensure this real-time functionality, several BMS implementations build on real-time operating systems (RTOS) like FreeRTOS or µC/OS-II, which switch tasks depending on priority and can provide guarantees regarding the time it takes to accept and complete a specific task

1.2 Overview of Available BMS and their Analysis

This section intends to give on overview of the battery management systems currently available on the market, with a focus on electric vehicle (EV) applications. These systems are then categorized and analyzed according to key parameters and the topological variants that have been defined in the previous section.

It should be noted that obtaining an overview over the various BMS that are currently available for commercial or academic purposes is difficult due to several reasons. First: there are different applications for BMS, and thus the BMS available on the market are often highly adapted to their application purpose. In this study, the focus is put on the intended use of the BMS in automotive applications; especially battery electric vehicles (BEV) and hybrid electric vehicles (HEV). Second: few information is publicly available especially for the BMS of larger OEMs and their suppliers for BEV and HEV applications, including some of the largest EV car makers like Volkswagen, Toyota, Renault-Nissan, and Tesla. Although these commercial systems have reached mass production levels and thus would be a very important part of the current BMS landscape, the respective companies currently keep most of the technical information about these systems – concerning topology, key specifications, software architecture, etc. – confidential, most likely because of fierce competition but also due to safety concerns. As far as possible, it was the aim for the study collecting at least information concerning the BMS of the EVs with the largest current market share in Europe. However, for many of these popular EV models, including Volkswagen e-Golf, Mercedes electric B-class, Renault Zoe, Chevrolet Bolt, Hyundai Ioniq, Opel Ampera/Chevrolet Bolt, BYD, and suppliers like Continental AG, Epower Electronics, Honda and Hyundai Kefico, the comparison remains incomplete as it turned out to be not possible to gather detailed enough technical information.

In contrast, smaller manufacturers and engineering companies that focus on BMS for prototypes, small batch and pilot series production, often provide adequately detailed information concerning the technical specification and structure of their BMS. For his reason, this analysis focuses mainly on this business sector. In addition, there exist some BMS platforms – including the systems from Altera, Fraunhofer, and LION Smart – that use open-source development strategies and focus mainly on research and early prototyping purposes.

1.2.1 List of the available BMS to be analyzed

Overall, from the research of the current state of the BMS market, the following list of 32 BMS has been compiled – in alphabetical order:

#1. Ashwoods Energy’s BMS (Vayon)
#2. AVL’s BMS
#3. Calsonic Kansei’s Nissan Leaf-BMS
#4. Delphi Automotive PLC Battery Management Controller
#5. DENSO’s Toyota Prius PlugIn-BMS
#6. Elite Power Solutions’ Energy Management System
#7. Elithion’s Lithiumate Pro
#8. Electric Vehicle Power System Technology Co., Ltd’s (EVPST) BMS-1
#9. Ford Fusion Hybrid’s BMS
#10. Hitachi’s Chevrolet Malibu Eco-BMS
#11. I + ME ACTIA’s BMS
#12. JTT Electronics LTD’s S-line
#13. JTT Electronics LTD’s X-line
#14. LG Chem’s Chevrolet Volt-BMS
#15. Lian Innovative’s BMS
#16. Lithium Balance’s S-BMS
#17. Lithium Balance’s S-BMS 9-16
#18. Manzanita Micro’s Mk3x-line
#19. Mitsubishi iMiEV’s BMS
#20. Navitas Solutions’ Wireless BMS (WiBMS)
#21. Orion BMS - Extended Size
#22. Orion BMS - Junior
#23. Preh GmbH’s BMW i3-BMS
#24. REAPsystems’ BMS
#25. Sensor Technik Wiedemann’s (STW) mBMS
#26. Tesla Motors’ Model S-BMS
#27. Tritium’s IQ BMS
#28. Valence U-BMS
#29. Ventec SAS iBMS 8-18S

Open research and prototyping platforms:

#30. Altera’s BMS
#31. Fraunhofer’s foxBMS
#32. LION Smart’s Li-BMS V4

The above-mentioned BMS have then been analyzed according to their key parameters, architecture, and other salient features. The complete list of analyzed features is given in Table 1.1

The detailed gathered information about these features for each BMS is given in the annex A. In the cases where the available technical documentation turned out to be too limited to identify these features, the respective table entries remain empty.

Topology	Classification of the BMS architecture regarding the previously identified subcomponents and topologies
Operation purpose	Battery Electric Vehicles (BEV), Plug-in Hybrid Electric Vehicles (PHEV), Hybrid Electric Vehicles (HEV) and other applications
Cell chemistry	Type of cell chemistries that can be handled by the BMS – a key limiting factor is the maximum and minimum cell voltage that can be monitored
Maximum pack size/ serial cells/ voltage	Maximum size of a battery pack – number of cells connected in series and/or maximum voltage that can be handled by the BMS
Features	Functions of the different BMS modules: measuring of voltage, temperature and current, protection, processing tasks, communication
Balancing current	Maximum balancing current (mA) for cell balancing
Power supply	Power consumption of the BMS modules and rated power supply
Communication	Available communication interfaces and specifications
Current measurement	Sensor type and location for pack current measurement
Main IC and characteristics	Type of microcontroller and its characteristics – measuring accuracy, resolution, sampling frequency
Additional features	Supplemental features exceeding the typical tasks of a BMS
Costs	Quotation price of the system modules
Certified standards	Standards and norms that are fulfilled by the BMS, or for which the BMS is ready
Location	Location of the BMS manufacturer
Quality of public information	Quality of publicly available information and documentation about the BMS (regular, good, excellent)

Table 1.1. List of considered BMS features.

In the following, an overview of the key features of each of the 32 considered BMS is provided.

#1: AshWoods Energy's BMS - now Vayon

The BMS from Ashwoods Energy is a modular system with multiple Battery Management Modules (BMM), a System Interface Module (SIM), and a CAN Current Sensor (CCS). The BMM combines properties of the PMU – SOC estimation, MMU – balancing – and CMU – voltage and temperature measurement – layer, whereas the SIM only shows PMU characteristics. It is needed for the communication with exterior controllers and enables charge and discharge mode. The CCS is used to measure the pack current and drive contactors of batteries with up to 1000 V. The application domain of this BMS are all possible variants of electric vehicles [52]. A diagram of this BMS is shown below in Figure 1.4.

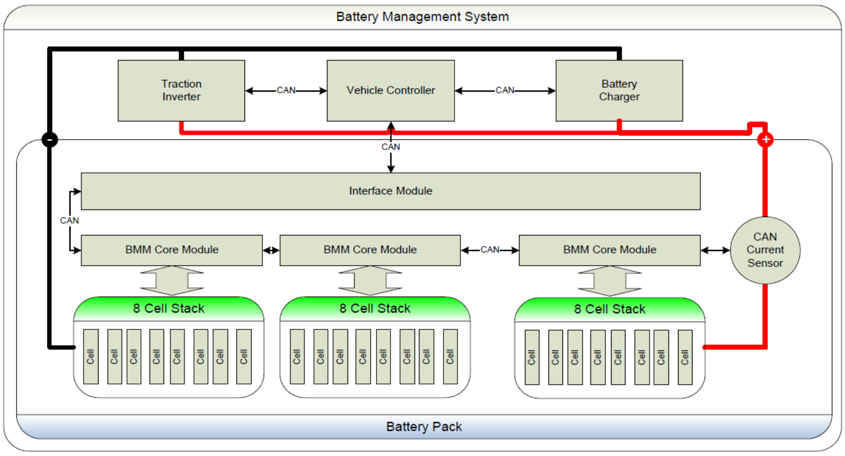


Figure 1.4. AshWoods Energy's BMS blocks diagram.

#2: AVL's BMS

AVL's modular Battery Management System consists of two layers called Battery Control Unit (BCU) as well as Module Control Unit (MCU) and is used for all automotive applications. While the MCUs measure cell voltages and temperatures, the BCU is meant to control those and perform all PMU functions. The maximum system voltage level is 800 V [53].

#3: Calsonic Kansei's Nissan Leaf-BMS

The BMS mounted in the Nissan Leaf has a centralized architecture. All CMU-, MMU- and PMU-requirements are fulfilled by one board that controls the 360 V system, which is quite uncommon for a battery of an all-electric vehicle [7].

#4: Delphi Automotive PLC Battery Management Controller

Delphi's modular Battery Management Systems are structured in a Hybrid and EV Controller and several Battery Management Controllers. The Hybrid and EV Controller acts as gateway between the battery and exterior vehicle controllers, whereas the Battery Management Controller provides all vital functions of a BMS for up to 450 V systems [54].

#5: DENSO's Toyota Prius Plug-In BMS

Toyota uses Denso's modular master-/slave-BMS for its PlugIn Prius. With four slaves, monitoring 56 serial cells, the battery works at a total pack-voltage of 207 V. One particularity of this BMS is, in contrast to all the other systems, the active balancing performed in the Toyota Prius Plug-In [7].

#6: Elite Power Solutions' Energy Management System

The company provides a BMS that shows a typical master/slave-topology. The master, called EMS-CPU, contains all PMU functions and controls a multitude of 4SB-V7, 4SB20-V2, or 4SB200-V7 Sense Boards. These are slave-boards which fulfills MMU and CMU features. With a total voltage of up to 500 V it is capable of managing BEV, PHEV and HEV batteries [55].

#7: Elithion's Lithiumate Pro

Elithion divides the tasks of the BMS between a controller called Lithium Pro Master – PMU functions – and either several cell-boards – CMU+MMU functions – for a single battery cell, or multiple cell-boards – CMU+MMU functions – that handle up to 16 cells in series. The maximum pack-voltage is restricted to 840 V and all EV uses are claimed to be possible [56].

#8: Electric Vehicle Power System Technology Co., Ltd. – EVPST – BMS-1

The BMS-1 contains a controlling module (CM) with PMU properties and up to four testing Modules (TM) with MMU and CMU qualities. The only advertised purpose of this 240 V system is the application in BEVs [57]. A diagram of this BMS is shown below.

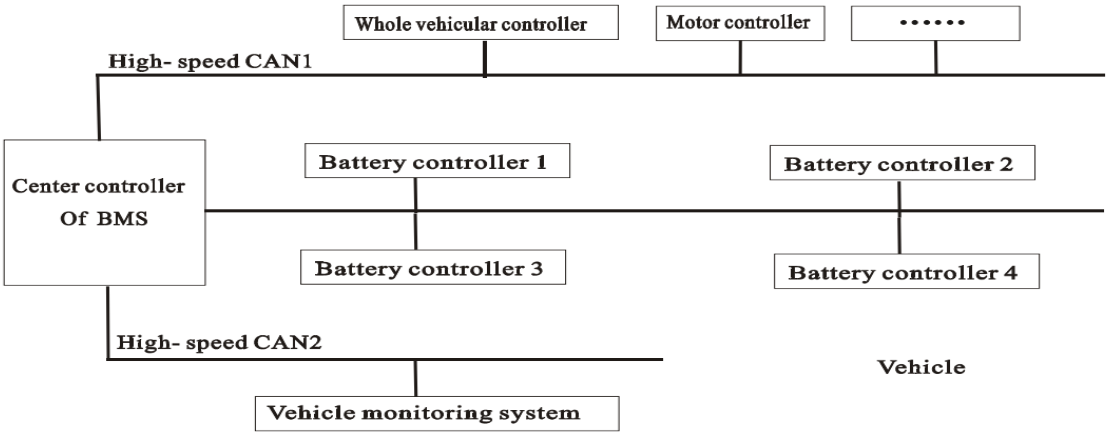


Figure 1.5. EVPST BMS-1 blocks diagram.

#9: Ford Fusion Hybrid's BMS

Ford uses a single centralized board, which satisfies all battery related tasks for the Fusion Hybrid. 76 serial cells in the battery add up to a total system voltage of 275 V [7].

#10: Hitachi's Chevrolet Malibu Eco-BMS

The combination of 32 serial cells create a pack-voltage of 115 V in Malibu Eco's battery pack. This system is supervised by a single, centralized battery management board [7].

#11: I + ME ACTIA

The BMS of I + ME ACTIA consists of a master 4.5 board and a set of slave 6 boards. The topology is clearly a modular master-/slave architecture and intended to be used in different EV applications [58].

#12: JTT Electronics Ltd. S-line

JTT Electronics provides two different systems for automotive applications: the S-series of BMS consists of 4 different centralized, stand-alone modules for different battery sizes (S1, S2, S3, S4). The S-line provides solutions for 55, 110, 165 and 200 volt, small EV exercises [59].

#13: JTT Electronics Ltd. X-line

For bigger vehicles, or in general applications that demand higher voltage levels, JTT supplies the X-line. This system combines an X-BCU – master – with several X-MCUP controllers – slave – to achieve all necessary functions of a BMS [59].

#14: LG Chem's Chevrolet Volt-BMS

LG Chem's modular BMS, consisting of one master and four slave boards, provides supervisory control for Chevrolet's Volt electric vehicle, where 90 serial cells sum up to 360 V at the pack level [7].

#15: Lian Innovative's BMS

Lian uses a modular architecture to form their BMS. It consists of a Power Control Unit (PCU), a Central Controller Unit (CCU) and Cell Boards (CB), either InnoCab, InnoLess, or InnoTeg. The Power Control Unit measures the pack voltage and current and connects/disconnects the battery to the load/charger, the Central Control Unit manages the remaining PMU tasks for all traction applications and up to 900 V. InnoLess are wireless cell-boards, each card is connected to one single cell. The InnoCab does the same, but wired and the InnoTeg board is a wired solution that senses five cells per card [60]. A diagram of this BMS is shown below in Figure 1.6.

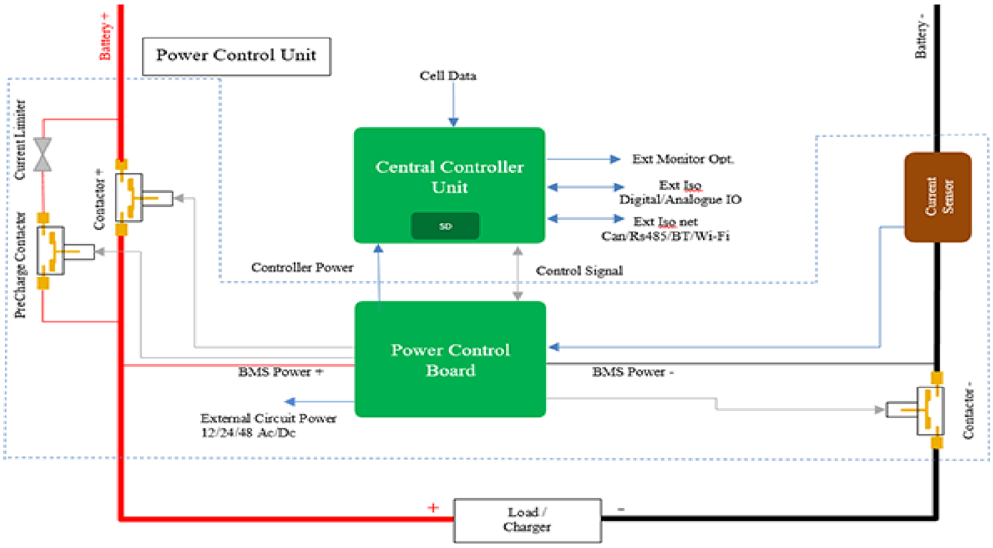


Figure 1.6. Lian Innovative's BMS blocks diagram

#16: Lithium Balance's S-BMS

The S-BMS is composed of a master board – Battery Management Control Unit – and monitoring boards – Local Monitoring Unit. S-BMS and S-BMS 9-16 show a conventional master-/slave-architecture with MMU+CMU- and PMU-functions on different boards. However, the S-BMS is capable to achieve pack-voltages of up to 1000 V for any automotive application [61].

#17: Lithium Balance's S-BMS 9-16

The modular S-BMS 9-16 in contrast is limited to 48 V packages. The supervision is achieved by two local monitoring unit and one battery management control unit [61].

#18: Manzanita Micro's Mk3x-line

Manzanita offers three different centralized systems of varying size – Mk3 Lithium BMS. Multiple boards of each system can be arranged in a row to increase the maximum pack-voltage – distributed system. Altogether, the boards can manage 120 (Mk3x4smt), 240 (Mk3x8), or 254 (Mk3x12) serial cells for any automotive application [62].

#19: Mitsubishi iMiEV's BMS

Mitsubishi's BMS makes use of a modular architecture with one master and 11 slave units. Each slave is able to monitor 8 serial cells, which results in a total pack-voltage of 330 V for the Mitsubishi iMiEV [7].

#20: Navitas Solutions' Wireless BMS (WiBMS)

Navitas offers a modular BMS for all automotive applications, which consists of a Battery Managing Module (MM) – master – and several Battery Sensing Modules (SM) – slave. Peculiar features of this BMS are the communication of Sensing Modules and Managing Module via wireless protocol – Wireless Local Area Network – as well as the possibility to reach pack-voltages of more than 1000 V [63]. A diagram of this BMS is shown below in Figure 1.7.

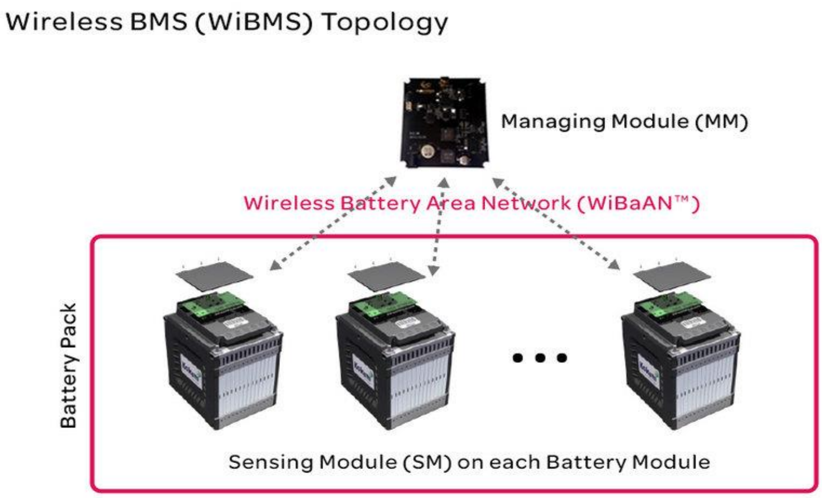


Figure 1.7. Navitas Solutions' Wireless BMS

#21: Orion BMS – Extended Size

The Orion BMS is a centralized system with the option to connect several boards in series – distributed topology – to achieve a larger system with voltages as high as 2000 V. All electric traction applications can be managed with this system [64].

#22: Orion BMS – Junior

Orion Jr BMS is a smaller version on the same basis without the possibility to form a distributed architecture. The designed use includes 48 V applications for light mobile traction devices [64].

#23: Preh GmbH's BMW i3-BMS

Preh supplies BMW's i3 with a modular BMS consisting of a master and 8 control boards – slave – boards. Every slave can monitor 12 serial cells, resulting in 96 serial cells and a total pack voltage of 360 V [7], [65].

#24: REAP Systems' BMS

REAP Systems produces a centralized Li-Ion BMS that is able to form a system in distributed topology for every automotive application. All single boards are able to handle 14 serial battery cells [66].

#25: Sensortechnik Wiedemann's – STW – mBMS

STW's mBMS is a modular, tripartite system. Its components comprise a Battery Main Supervisor with PMU functions – SOC/SOH estimation and voltage/temperature/current control – a Power Measurement Board (PMB), which also fulfills some PMU tasks – disconnect switch, current monitoring – and several Cell Sensor Circuits (CSC). With a maximum pack-size of 800 V, this BMS is capable of addressing all electric traction applications [67]. A diagram of this BMS is shown below in Figure 1.8.

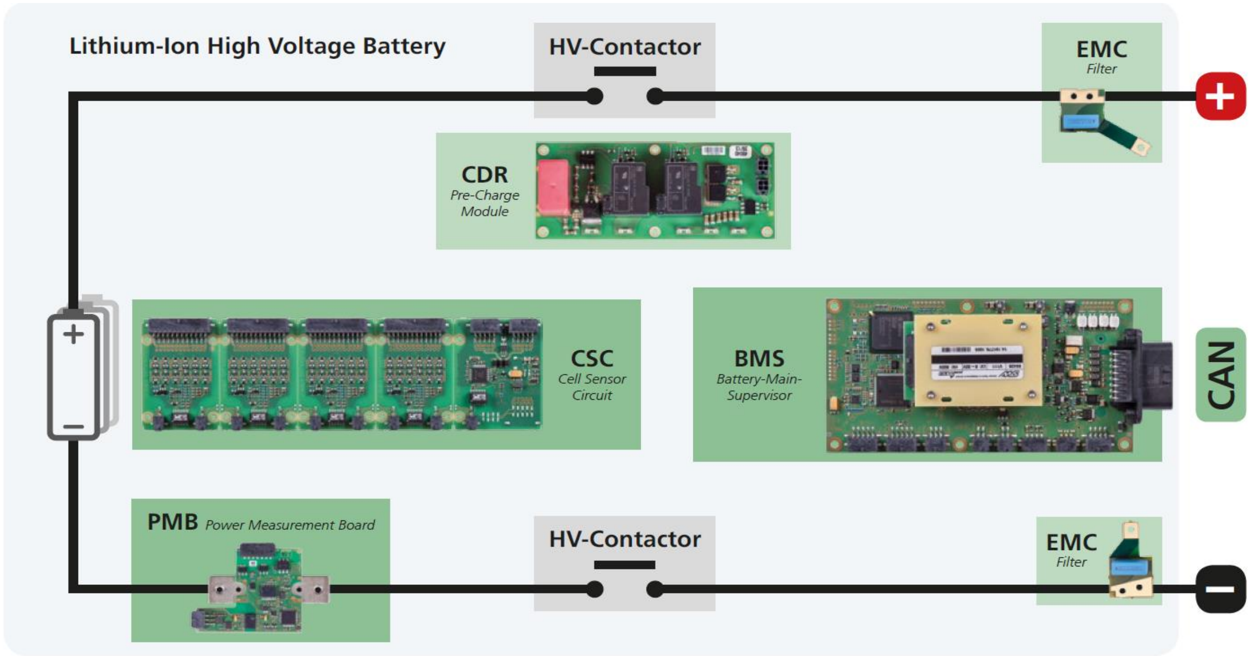


Figure 1.8. STW's BMS.

#26: Tesla Motors' Model S-BMS

Another example for a typical modular, master/slave-architecture is the BMS of the Model S from Tesla Motors. All 16 slaves are able to measure values of 6 serial cells, resulting in a 400 V system with 96 cells in a row [68].

#27: Tritium's IQ BMS

Tritium's IQ BMS also represents a typical master/slave-architecture with a Battery pack Management Unit (BMU), which acts as master, and several Cell Management Units (CMU), which function as slaves. Up to 256 cells can be combined in series in order to form a 1000 V battery-pack [69].

#28: Valence U-BMS

Valence offers four centralized system variants for different battery sizes: U-BMS-LV, U-BMS-LVM, U-BMS-HV and U-BMS-SHV. The U-BMS-LVM allows multiple units to be connected to a distributed system up to 1000 V. The others are used for 150 V (-LV), 450 V (-HV), or 450 V (-HV) automotive applications [70].

#29: Ventec SAS i-BMS 8-18S

The iBMS 8-18s is Ventec's only System for automotive applications – small electric vehicles. It has a centralized, distributed structure. Every single module handles 18 cells, the total pack-voltage is limited to 1000 V [71].

#30: Altera's BMS

Altera offers a flexible FPGA-based control platform that can be configured by the customer, resulting in improved performance and efficiency. It is able to estimate the SOC, SOH with a Kalman filter for 96 serial cells [72], [73].

#31: Fraunhofer's fox BMS

Fraunhofer's foxBMS is a flexible, also FPGA-supported BMS platform, which normally works with fox BMS master and fox BMS slaves. However, it is also possible to leave out the slaves and thereby get to a system with centralized architecture, where CMU and MMU properties are also covered by the master module [74], [75].

#32: LION Smart's Li-BMS V4

The BMS of LION Smart consists of a master – Lion Control Module – and several slaves – Lion Measure Module – and follows the typical structure of a modular system with a combined CMU/MMU-unit and a separate PMU-unit. It is technical possible to connect 16 slaves, 12 serial cells apiece, to form a battery with up to 800 V for EV applications. The Li-BMS V4 offers an open source code based for software adjustment by customers [76].

1.2.2 Analysis of the available BMS

Hardware Topology

One of the salient characteristics of a battery management system is its hardware topology. As mentioned above, this comprises the structure and organization of the different boards, which are needed to fulfill all tasks of a full-fledged BMS. First, the various examined manufacturers and their BMS have been classified as modular and centralized. Furthermore, the centralized systems can be sub-grouped into BMS that can be used to build a distributed topology, and those that cannot – see Table 1.2.

Modular architecture	**Centralized architecture**
#1: Ashwoods Energy's BMS (Vayon)	#3: Calsonic Kansei's Nissan Leaf-BMS
#2: AVL's BMS	#9: Ford Fusion Hybrid's BMS
#4: Delphi Automotive PLC BMC	#10: Hitachi's Chevrolet Malibu Eco-BMS
#5: DENSO's Toyota Prius PlugIn-BMS	#12: JTT Electronis LTD's S-line
#6: Elite Power Solutions' EMS	#21: Orion BMS – Extended Size
#7: Elithion's Lithiumate Pro	#22: Orion BMS - Junior
#8: EVPST'S BMS-1	#28: Valence U-BMS
#11: I + ME ACTIA's BMS	
#13: JTT Electronics LTD's X-line	
#14: LG Chem's Chevrolet Volt-BMS	**Distributed architecture**
#15: Lian Innovative's BMS	#18: Manzanita Micro's Mk3x-line
#16: Lithium Balance's S-BMS	#24: REAPsystems' BMS
#17: Lithium Balance's S-BMS 9-16	#28: Valence U-BMS-LVM
#19: Mitsubishi iMiEV's BMS	#29: Ventec SAS iBMS 8-18s
#20: Navitas Solutions' Wireless BMS	
#23: Preh GmbH's BMW i3-BMS	
#25: Sensor Technik Wiedemann's mBMS	
#26: Tesla Motors' Model S-BMS	
#27: Tritium's IQ BMS	
#30: Altera's BMS	
#31: Fraunhofer's foxBMS	
#32: LION Smart's Li-BMS V4	

Table 1.2. Classification of available BMS according to their topology.

Next, other salient features for the list of available BMS have been analized. However, due to the lack of technical details for some of the BMS, not all of the necessary information is available and therefore it is not possible or reasonable to draw a conclusion for all these features.

Topology and Operation Purpose

The list of available BMS comprises 32 systems of 29 different manufacturers. It has been found that 10 of these systems exhibit centralized topologies, while 22 have a modular one – see table 1.2. Additionally, some of these 10 centralized BMS systems can be subdivided into different centralized variants. Taking into account all the variants of the centralized BMS for different voltage levels, it sums up to 18 centralized systems out of 40 BMS in total. Since modular architectures do not need explicitly different variants to achieve control over different levels of battery pack voltages – it is sufficient to add the required number of PMU or CMU boards – the number of 22 BMS represents the total number of stand-alone systems. As noted before, centralized systems offer a simple and, for a certain requirement, cost-efficient solutions, but limited scalability [77], [78].

The analysis shows only 7 BMS which are not explicitly intended to operate in BEVs; consequently, they do not work with high voltage levels. 5 of them have a centralized structure. Furthermore, 20 of the 22 modular BMS that have been considered in the analysis are intended to manage battery packs for BEVs. 13 out of 18 centralized systems are specified to be only suitable for applications of 200 volts and below.

Although some of these centralized BMS allow to be interconnected establishing a larger-distributed topology, high-voltage applications are more likely to be addressed by modular BMS, partly because it is more challenging to handle insulation in a centralized system compared to several subsystems with lower voltage levels [6]. An exception is the 360 V system of the Nissan Leaf [7]. However, a disadvantage of modular systems is the large number of communication and power supply circuits needed and the resulting, comparably high costs [8].

The costs overhead is even higher for distributed systems with multiple instances of centralized boards, as there are inevitably redundant components on the boards [9]. This is possibly the reason why this topology has been found to be not so widespread in this study.

Additional Applications

The requirements that different applications pose on a BMS seem to be often similar, as many BMS in the list are capable to work in at least one additional operation context. 25 of the 30 pilot-batch-BMS are, besides automotive use, also advertised to work in other applications like stationary storage, power backup, or marine vehicles.

Cell Chemistry

The main restricting factor for the use of a BMS with different cell chemistries is the maximum cell voltage that can be measured per CMU channel. The maximum voltage of lithium-iron-phosphate cells is 3,65 V – one of the lowest for all lithium-ion cell chemistries – whereas for the wide-spread nickel-manganese-cobalt cells it is 4,2 V. As a result, all lithium-iron-phosphate batteries can be managed by any of the listed lithium-ion BMS. 28 of the 30 analyzed pilot-batch Battery Management Systems can operate all common lithium-ion cell chemistries. Only two systems are designed to work exclusively with lithium-iron-phosphate cells [79].

Communication Interfaces

Almost every considered BMS uses at least one CAN-bus communication line, only the BMS of Manzanita Micro (#18) and Navitas Solutions (#20) present no evidence of the possibility to communicate via CAN-bus. The reason for this wide-spread use of the CAN-bus might be the easy interfacing to other controllers in the automotive environment, which often already use CAN communication [10].

Wireless BMS (e.g. #20) layouts, which replace the internal communication between the modules with wireless network, can have potential advantages including reduced cable harnesses, connectors and wiring effort during assembly. However, a challenge of wireless BMS is the possible disturbance of the wireless network by electro-magnetic noise from within the car [11] and outside entities, which may create safety and security issues.

Other Features

Many of the systems offer additional PC-based software to adjust the BMS settings and parameters for the application at hand. Such tools are especially important for pilot or small batch series and open research platforms.

Market Regions

37 out of the 39 BMS variants – of which the location could be identified – are from manufacturers located either in Western Europe, North America, Japan, or China. The only two notable exceptions are Tritium (#27) with its headquarter in Australia, and LG Chem (#14) in South Korea.

2 Functional safety processes for automotive BMS design

2.1 Functional Safety in Vehicles – ISO 26262:2011

A Battery Management System or BMS fundamentally constitutes a safety component. In the last two decades, electrical and electronic (E/E) systems have become more complex due to their high degree of integration and networking [80]. As a result, the state of the art for essential safety functions can often only be achieved with great effort in the development of hardware and software.

There are standards, directives and laws, which must be accordingly applied or complied with. They are determined by the specific applications and defined within their scope. A BMS can be used, for instance, in energy storage systems for houses or in hybrid or all-electric vehicles. Consequently, different areas have to be covered: on the one hand, stationary energy storage applications; on the other hand, automotive. For this reason, either the general industry standard IEC 61508 – Functional safety of safety-related electrical/electronic/programmable electronic systems – or the ISO 26262 Road vehicles – Functional Safety can be applied to a BMS [12], [13]. Compared to stationary systems, more application scenarios and therefore possible failures can occur in vehicles. In order to be able to use the BMS specifically in the automotive sector, the ISO 26262 standard is the choice of election [12], [13].

In 1998, the generic IEC 61508 standard was published. Since a generally valid standard for functional safety of E/E systems was then available, an attempt was made to apply it to vehicles. In 2002 BMW started to develop a standard adapted for vehicles in a German-French cooperation [80]. As of 2005, the management was transferred to ISO and delegated to the Standards Committee of the German Institute for Standardization (DIN). After various drafts and phases for comments and changes, the standard ISO 26262 was published in 2011. Since then, it has been formally legal as a valid standard for road vehicles [80]. The ISO 26262 standard represents the state of the art of technology and is thus a recommendation for procedures for new developments. For safety functions, the state of the art must be complied with, in order to achieve the minimum required safety level.

This section introduces and explains important terms of ISO 26262. A comprehensive overview of the different parts of the standard is given. As a special case, it will be exemplified how functional safety in an automotive BMS can also be achieved, according to the standard. In the corresponding subsections of this study, the recommended methods to be applied for prototyping, at different stages of the development processes, are also addressed.

2.2 Scope and Definition of Basic Terms of the Standard

The scope of ISO 26262 – Road Vehicles – Functional Safety refers to safety-relevant systems that contain at least one E/E system and are located in a standard passengers car, with a vehicle mass of up to 3500 kg [81]. Explicitly excluded are unique E/E systems in special purpose vehicles, such as vehicles for persons with physical impairment. Therefore and strictly speaking, the standard is not applicable to prototypes as they are unique E/E systems.

In addition, components or systems and their components, which were released for production prior to the publication date in 2011 or had already been developed, are exempted from the standard. The scope of the standard excludes hazards such as electric shock, fire, smoke, heat, radiation, poisoning, inflammation, chemical reaction, corrosion, emission of energy and comparable hazards, as long as they were not caused by a malfunction of an E/E safety-relevant system [81]. Moreover, intentionally induced malfunction is not an objective of ISO 26262 [82]. Although a standard for functional performance for active and passive safety systems exists, the nominal performance of E/E systems is not addressed in ISO 26262 [81], [83], [84]. This is explicitly stated in the preface of the standard.

According to traffic safety regulations in some European countries, a product or its development must correspond to the state of the art when placed on the market. See ProdSG – Product Safety Act [85], for example. And in the case of product liability, the manufacturer shall provide proof of safety. In accordance with §476 BGB from the German Civil Code, for instance, it is necessary to furnish proof that the components or products used have been developed in accordance with the applicable standards and regulations, as well as with the state of the art. And since ISO 26262 is regarded as the state of the art as from publication, it must be taken into account for the reasons above mentioned [80]. According to the Court's judgement VI ZR 107/08 of the Federal Court of Justice of 16 June 2009 [86] a system is not permitted to exert a greater risk than would have been avoidable by the state of art.

2.2.1 Functional safety definition

Functional safety is generally described as a correct technical reaction of a technical system, in a defined environment, for a given defined stimulation at the input of such technical system [87]. Instead, the term functional safety is defined in ISO 26262 as freedom from unacceptable risks, due to hazards caused by malfunctions of an E/E system [81]. And it is mandatory that a component or a system is transferred to a safe state should a failure occur.

In order to guarantee and justify freedom from unacceptable risks, the functional safety development procedure is applied as stated in ISO 26262 [88]. Main concepts here are the abstract item's safety goals, which are explained in more detail in subsections 4.24 and 4.3.1. At that level of the application of the standard, the vehicle and its items are observed in their environments. In subsection 4.2.4, functional safety requirements in the functional safety concept for the vehicle and its implemented systems are defined. These must fulfil the requirements of the safety goals. At the next more detailed level of the specific E/E systems, technical safety requirements in the technical safety concept are developed as well, which again must meet the functional safety requirements – see subsection 4.3.2. The last step is to create safety requirements for hardware and software that are intended to ensure freedom from unacceptable risks at components and part levels [88]. A simplified representation of the critical route to follow on the application of the ISO 26262 standard, aiming to achieve freedom from unacceptable risk during the life cycle of automotive E/E systems, is shown as a block diagram, in Figure 2.1.

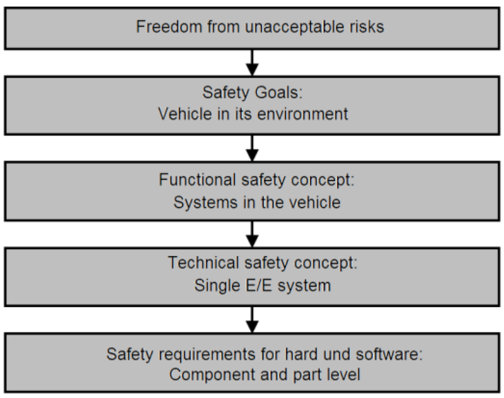


Figure 2.1. Targeting freedom from unacceptable risk with the functional safety development procedure.

2.2.2 Faults, errors and failures definitions

On the proper application of the ISO 26262 standard, the following concepts of fault, errors and failures, as well as their cause-effect relationships need to be observed.

- Fault: Abnormal condition that can cause an element, function unit or a vehicle system to fail [81].
- Error: Discrepancy between a computed, observed or measured value or condition, and the true, specified or theoretically expected, correct value or condition [81].
- Failure: Termination of the ability of an element to perform a function as required [81].

Hence, lie on these concepts an implied cause-effect relationship, which links them. As can be seen in Figure 2.2, a fault can cause an error, which can lead to a failure of a function unit or a system.

Figure 2.2. Relationship between fault, error and failure.

When considering functional safety according to ISO 26262, basically two types of faults, errors and failures can be distinguished: random and systematic [87]. Systematic ones can be avoided by appropriate methods in the design process, whereas random ones can only be reduced to a tolerable degree. Systematic or even random failures can occur with hardware. Failures in the software, on the other hand, are strictly systematic [87].

Failures can also be divided into another two different categories. If a single fault results in a deviation of a calculated, observed or measured value or state, thereby being solely responsible for a failure of a total system, the term single-point failure is used. In the case of a multiple-point failure, however, several independent individual faults lead to a failure [87]. A special case of the multiple-point failure is the double-point failure caused by two mutually independent individual faults. ISO 26262 addresses these aspects concerning failures by means of the so-called safety goals and not from the possible, direct impact of the failures on the system's behavior.

Further faults definitions are provided in the standard: detected faults, latent faults, perceived faults, permanent faults, residual faults, transient faults and safe faults. The latter, for instance, seems to be a contradiction in terms; however what it is meant is that the occurrence of these faults does not significantly increase the likelihood of infringing a safety requirement. The term residual fault is used when a fault that occurs in the hardware leads to a violation of a safety goal, but it is not covered by any security mechanism [81].

For the occurrence of a faults, also temporal relationships are defined in the standard. The diagnostic test interval describes the amount of time between the executions of online diagnostic tests by a safety mechanisms. The fault reaction time is the time-span from the detection of a fault, until reaching the safe state. These temporal relationships can be seen in Figure 2.3.

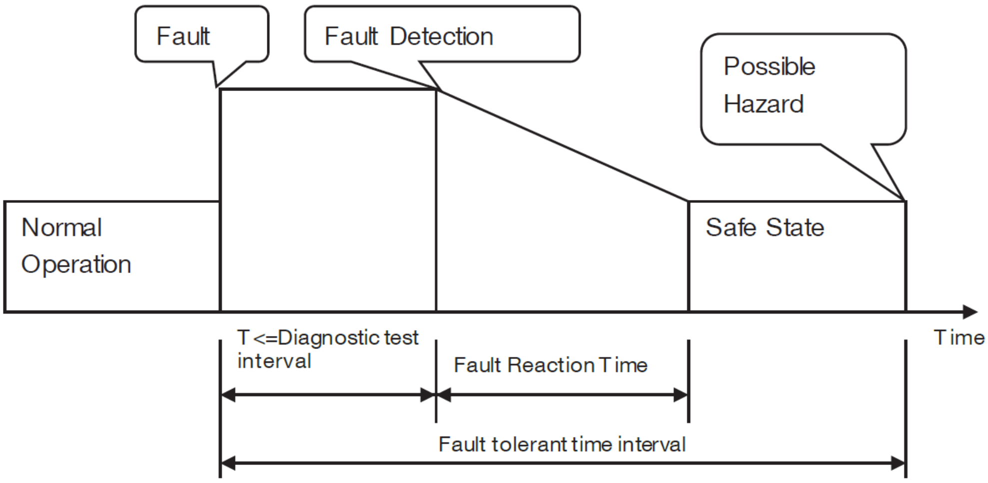


Figure 2.3. Relationship between fault occurrence, fault detection und fault reaction time for reaching the safe state [81].

2.2.3 Risk definition

According to [89], a risk (R) can be described as a function (F), with the frequency of occurrence (f) of a hazardous event, the ability to avoid specific harm or damage through timely reactions of the involved persons – that is the controllability (C), and the potential severity (S) of the resulting harm or damage. Mathematically, it can be formally defined as follows:

$$R = F(f, C, S) \tag{1.1}$$

The frequency with which a damage occurs is defined as the product of the exposure (E) of the persons involved in a dangerous situation and the failure rate of the item that could lead to the hazardous event (λ).

$$f = E \cdot \lambda \tag{1.2}$$

Since a BMS monitors lithium-ion accumulators, the hazard levels according to EUCAR [90] can be used to describe safety-critical events – see Table 2.1. They classify the events during safety tests of Li-Ion accumulators regardless of their cause [90].

Description	Hazard-Level
No effect	0
Passive protection activated	1
Defect / Damage	2
Leakage with mass loss < 50%	3
Venting with mass loss ≤ 50%	4
Fire or Flame	5
Rupture	6
Explosion	7

Table 2.1. EUCAR hazard levels and their description [90].

These events can also occur when e.g. protective devices of the cells no longer function and when they are outside the specification limits. The objective of ISO 26262 is to avoid personal and environmental damage as far as possible. Therefore, events from hazard level 5 and higher are classified as critical [91]. Due to potentially toxic gases [46], the respiratory tract can already be injured from level 3, or the environment can be polluted. It might then be advisable to specify a maximum permissible hazard level for the cells used in a battery pack, as in [91] for example, at a level lower than 5.

In order to achieve the objective of reducing harm, ISO 26262 also attempts to systematically reduce the initial risk to a minimal residual value, which is below an acceptable or tolerable risk [87] – see Figure 2.4. The normative derivation of the initial risk is carried out in ISO 26262, part 3, paragraph 7 using a so-called hazard analysis and risk assessment.

2.2.4 Item definition, Automotive Safety Integrity Levels – ASIL, safety goals and safety requirements

As shown in Figure 2.5, hazard analysis and risk assessment can be used to find different scenarios in operating situations and operating conditions as a first step. In step 2, all malfunctions assigned to the scenarios, which could lead to dangerous situations, are searched for. As a result, an Automotive Safety Integrity Level (ASIL) can be determined for the respective hazardous situations in step 3. According to [92], even more concrete and more limited usage scenarios can be defined here for prototypes. In this way, the experimental space – e.g. test sites – and the duration of use can be restricted. By additionally defining the necessary driver qualification, the prototype quality level (PQL); analogous to the ASIL – proposed for prototypes will receive a lower estimate. And fewer measures for risk reduction are effectively needed.

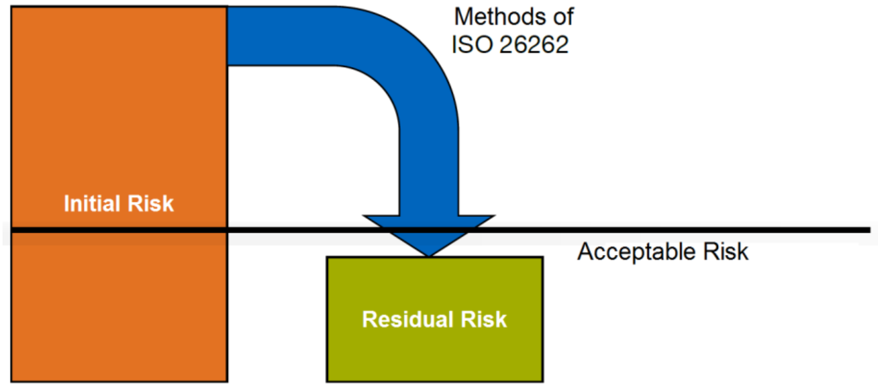


Figure 2.4. Minimizing the initial risk to a residual risk employing ISO 26262.

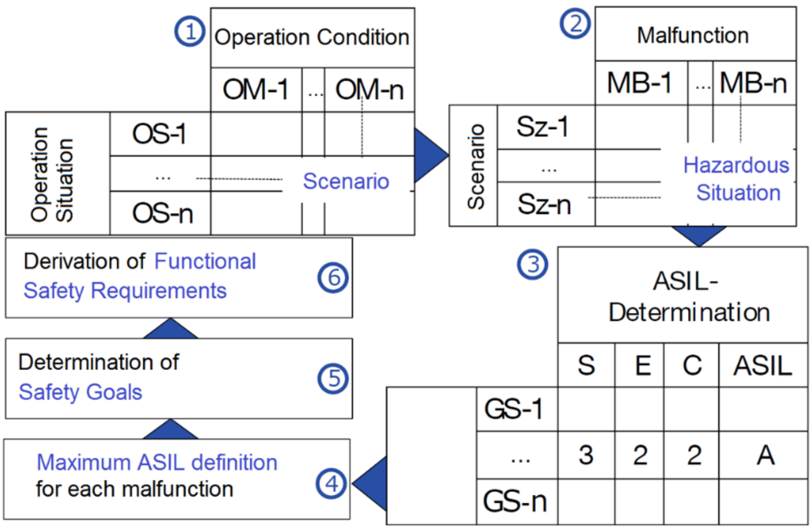


Figure 2.5. ISO 26262-3 Scheme ©TÜV Süd [93].

According to [81], ASIL levels can be grouped in four levels, in order to define the necessary requirements for the vehicle's system or individual functional units, in such a way that unacceptable residual risks are avoided. In the fourth step, the maximum ascertained ASIL is determined for each found malfunction. Based on the malfunctions, safety goals can then be derived as a result in working step 5. Also according to [81], a safety goal is a safety requirement at a top level, which is a direct outcome from the hazard analysis and risk assessment. It can refer to several risks, but different safety goals can also be assigned to a unique risks [81]. Following the definition of the safety goals, the corresponding functional safety requirements can be derived in step 6.

According to [2], [94], a tailoring of the ISO 26262 process observed in Figure 2.5 to the BMS, as part of the automotive energy storage system, could be the application of the methodology of a safety element out of context (SEooC), meaning this the application of the standard to the design of the safety life cycle without taking into consideration other related items of the vehicle. In this sense, it is of paramount importance a description of the preliminary design in as much detail as possible, because it constitutes the input to the next safety related, design activities. That is, the definition of the item.

According to [94], the item definition step should clarify the boundaries of the product under development and document the preliminary assumptions about the item's components and functionalities. To define a specific item, usually simple block diagrams showing the item's key elements are employed. These diagrams constitute a preliminary and simplified architecture definition, provided as examples in order to establish the concepts. From [94], the block diagram corresponding to the hypothetical item Lithium-ion battery system is shown in Figure 2.6 a). In this example, the item is composed by the main elements battery cells, the cells balance interconnect module, the high voltage contactor module and the BMS. The BMS comprises, in turn, the generic sensor input processor in charge of converting sensed analog signals from the battery cells to a digital format, and the battery controller, which performs SoC and SoH calculations and controlls the cells equalization tasks. From [37], Figure 2.6 b) shows the block diagram corresponding to the item definition for a safe energy storage system, for small electric vehicles.

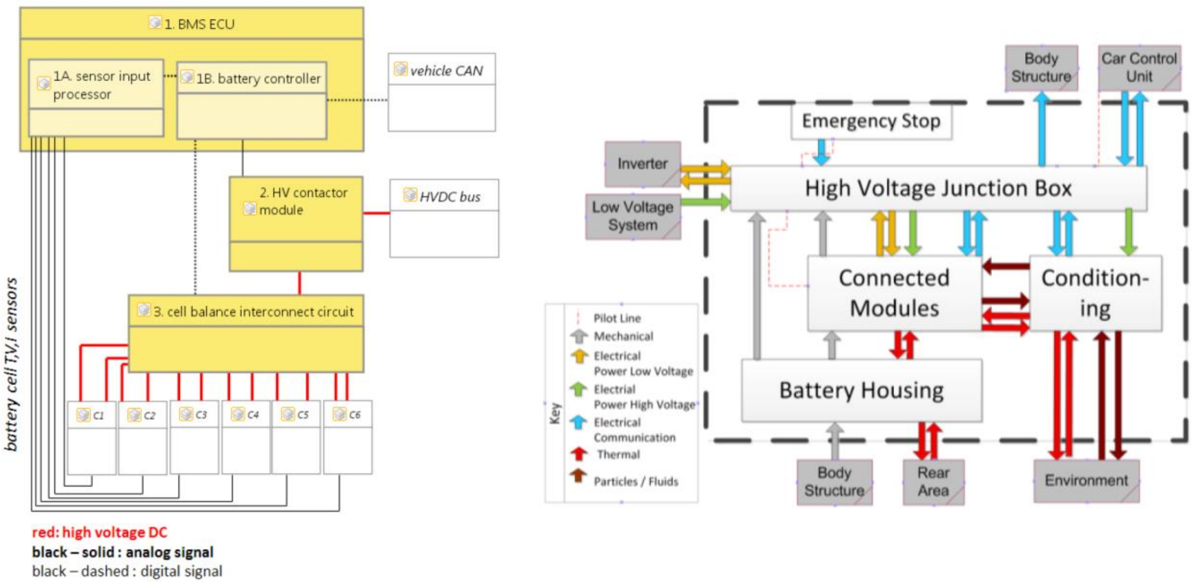


Figure 2.6. Block diagrams for the item definition. a) Preliminary architecture of the hypothetical Li-ion battery system [94]. b) Key elements and signals within the energy storage system [37].

According to [37], for the assessment of the specific case of lithium-ion based energy storage systems during the item definition step, multiple schematic diagrams beginning from the superordinate groups to each lower level component in the hierarchy can be issued. While Figure 2.6 b) shows the top of four levels, Figure 2.7 a) and b) show the representation in block diagrams of the connected modules and of one generic specific module.

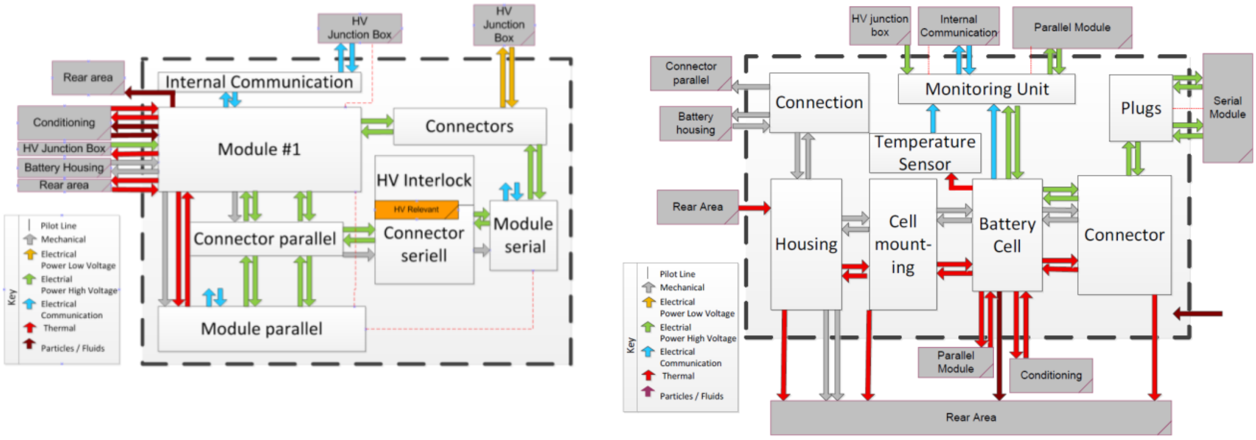


Figure 2.7. a) Signals and blocks within the block diagram connected modules in Figure 2.6 a). b) Signals and blocks within module # 1 [37].

Also for the item definition, specifying the interfaces for the item is an important part of the step. In case of the example provided in Figure 2.6 a), the high voltage DC bus, as well as the vehicle CAN bus – or other communication busses allowing the exchange of information between the BMS and other vehicular systems – are there exemplified. The item definition should describe these interfaces as clear as possible providing, for example, voltage levels and power capabilities of the high voltage DC bus, the CAN protocol and the specific signal information.

The proper item definition comprises not only a description of its known or expected functionalities, but also a description of the malfunctions of the item. These are critical to clearly understand what the item should or should not do. For instance, it can be noticed that, while the battery provides and accept power to and from the high voltage DC bus, the power flow is, in most of the cases, not actively controlled by the BMS. The current flowing to and from the high voltage bus will be determined, at any given time, by the powertrain controller, the battery charger or the motors' inverter. However, flow and power can be always enabled or disabled by controlling the main high voltage contactor. The limitation of the cells temperature can be understood as an additional example. The BMS only monitors the cells current, voltage and temperature, while is able to operate the battery's active cooling systems.

An exemplary summary of the known functionalities and mal functions for the item block diagram provided in Figure 2.6 a, is shown in Table 2.2. Table 2.3 shows quantitative indicators for the item in Figure 2.6 b).

FUNCTION F001: Provide Power to HVDC Bus	
malfunction mf001	power not provided to HVDC bus when required
malfunction mf002	unintended power delivery to HVDC bus
FUNCTION F002: Accept Power from HVDC Bus	
malfunction mf003	Power from HVDC bus not accepted as required
malfunction mf004	Charging of battery pack beyond allowable energy storage
malfunction mf005	Charging of battery pack beyond allowable current
FUNCTION F003: Limit Cell Temperatures	
malfunction mf006	cell overtemperature due to internal short
malfunction mf007	cell overtemperature due to thermal management failure
malfunction mf008	cell overtemperature due to overcurrent

Table 2.2. List of some functions and malfunctions of a hypothetical Li-ion battery system [94].

Component cluster	Component(s)	Number of Functions	Number of Mal-functions
Battery housing	Battery housing	**6**	**6**
High-voltage junction box	Isolation guard, electronic monitoring unit master, current sensor, fuses, contactor „Drive +“, contactor „Drive –„, contactor „pre“, contactor „DCDC“, Preload resistance, plugs, housing	**44**	**62**
Conditioning	Fan, air duct components	**6**	**7**
Emergency stop	Emergency stop	**3**	**4**
Connected modules	Internal data transmission, electronic monitoring unit module, connection, housing, cell mounting, connectors, plugs, temp. sensors, board connectors parallel, board connectors serial, HV-Interlock	**34**	**57**
Totals	28 components	**93**	**136**

Table 2.3. Range of the item definition, number of component functions and amount of malfunctions [37].

Building on the definition of the item, the hazard analysis and risk assessment can be conducted, aiming for the identification and categorization of the malfunctions and hazards which are strictly related to the proper operation of the BMS – step 2, Figure 2.5. Once these hazards and malfunctions are identified, they are also classified according to their controllability (C) and the severity (S) of the potential harm to the vehicle occupants, the people outside and the environment. Within this analysis are falling as well the driving situations and the exposure (E) to that driving situation, since the threats each hazards poses to persons are driving situations dependent. Here is where ASILs are determined – step 3. An excerpt from a hypothetical and simplified hazard analysis and risk assessment found in [2] is shown in Table 2.4, to exemplify the process only for the case of the deep discharge hazard.

Driving situation	Hazard	S	E	C	ASIL
Slow driving	Deep discharge causes internal short and fire of battery pack	S3	E3	C1	A
Urban driving	Deep discharge causes internal short and fire of battery pack	S3	E4	C2	C
Extra urban driving	Deep discharge causes internal short and fire of battery pack	S3	E3	C3	C

Table 2.4. Part of a simplified hazard analysis and risk assessment for the hypothetical BMS [2].

In a similar manner, [94] also provides a limited subset of potential hazards to take into consideration, incorporating in this example the related malfunctions to the specific hazard: Overcharge causes thermal event. Further and analogous hazards, such as those related to battery overcurrent or over-temperature, can be here considered as well. It should be noticed for the examples in tables 4.4 and 4.5, that controllability is heavily influenced and in consequence assessed by taking into consideration the ability of the driver to quickly stop the vehicle in a safe location, and exiting the car along with all the passengers. For the case of overcharging the battery, the related malfunction could occur when recovering energy while braking; or while charging the battery pack from the internal combustion engine in hybrid vehicles.

Driving situation	Hazard	Malfunction	S	E	C	ASIL
Speed <10 km/h	Overcharge causes thermal event	Charging of battery pack beyond allowable energy storage	S3	E3	C1	A
Speed >10 km/h <50 km/h	Overcharge causes thermal event	Charging of battery pack beyond allowable energy storage	S3	E4	C2	B
Speed >50 km/h	Overcharge causes thermal event	Charging of battery pack beyond allowable energy storage	S3	E3	C3	C

Table 2.5. Excerpt from a simplified hazard analysis and risk assessment [94].

For the summary of components, functions and malfunctions provided in Table 2.3, the combination of 23 realistic operational scenarios – throughout the vehicle's life cycle – together with the 136 identified malfunctions, has yield a total of 3128 possible hazardous events [37]. The 23 realistic operational scenarios have been achieved by linking operational locations – subterranean garage, small streets, middle streets, large streets, highway and motorway, etc. – together with operational conditions – parking, ignition off, vehicle ready, gear engaged, brake actuated, rolling, acceleration, braking/regeneration, Stop and Go traffic, maneuver with full lock, constant driving, etc. An excerpt of the most threatening malfunctions here found are listed in Table 2.6 and ASIL has been assigned to them, achieving with this methodology a clear overview of the most relevant hazards that could affect the safety of the energy storage system. It is explained in [37], that after detailed consideration by an experts committee, only 142 hazardous events were selected from 3128, because although a large number, many have a similar threat potential. The experts committee was conformed by engineers with experience in lithium-ion cells, BMS, battery system design and field application, as well as professionals in the methodological approach to the hazard analysis and risk assessment.

Malfunction	Maximum ASIL
Destruction of housing	B
Possible threat of high voltages	C
Failure of cell monitoring	D
Unknown current load	QM
Interruption of HV circuit not possible	D
Overcharging	D
Insufficient cooling	A
Failure activation of emergency stop	B
Failure of data transmission	C
Destruction of cell mountings	C
Mechanical, electrical or thermal overload of cell	D
Tear off bonding, sense and sensor conducts	D
High temperatures in energy storage system	C

Table 2.6. ASIL assessment of major malfunctions [37].

As in steps 4 and 5 of Figure 2.5, for each identified hazard that was subsequently linked with the maximum of all the determined ASILs, safety goals have to be defined as well. This is exemplified in Table 2.7 for the case of a BMS. These are yet no technical solutions for the issues presented by the hazards; rather functional objectives for the BMS.

ID	Safety goal	ASIL
SG1	Deep discharge of one or more cells in the battery pack shall be prevented	C
SG2	Overcharge of one or more cells in the battery pack shall be prevented	D
SG3	Over temperature of one or more cells and the management electronics in the battery pack shall be prevented	D
SG4	Unintended presence of HV at battery pack poles shall be prevented	B

Table 2.7. Partial list of safety goals applicable to an automotive BMS [2].

In the examples of figures 4.5 to 4.7 and tables 4.2 to 4.7, ASILs are defined by making use of the criteria severity (S), exposure (E) and controllability (C). Each of these three criteria are rated beginning with 0; which respectively means that a dangerous situation does not cause injuries, is unthinkable, or generally controllable. The ratings of S and C correspondingly are S0-S3 and C0-C3, while the frequencies of exposure to the risky situation are rated as E0-E4. The rating of these three partial evaluations could also be reduced by discussion and a preferably conservative assessment could result. The proper ASIL can be directly derived from the sum of partial evaluations as shown in Table 2.8 or by means of the qualitative method of the risk graph – Table 2.9 – being ASIL A the lowest and ASIL D the highest necessary integrity level, accordingly assigned to a risk potential.

Therefore, with an ASIL level D, methods and measures for risk reduction are most frequently required as compared to the other levels. If the sum of the partial evaluations is less than or equal to six – Sum S+E+C in Table 2.8, it is assumed that a quality management systems established within the company suffice in order to prevent failures in the sense of functional safety [80], [95], [96]. Subsection 4.4 approaches quality management.

Sum S+E+C	7	8	9	10
ASIL	A	B	C	D

Table 2.8. ASIL levels derived from summing criteria S, E and C [97].

The results from Table 2.8 can be visualized in the so-called risk graph – Table 2.9.

		C0	C1	C2	C3
S0	E0 – E4	QM	QM	QM	QM
S1	E0	QM	QM	QM	QM
	E1	QM	QM	QM	QM
	E2	QM	QM	QM	QM
	E3	QM	QM	QM	ASIL A
	E4	QM	QM	ASIL A	ASIL B
S2	E0	QM	QM	QM	QM
	E1	QM	QM	QM	QM
	E2	QM	QM	QM	A
	E3	QM	QM	ASIL A	ASIL B
	E4	QM	ASIL A	ASIL B	ASIL C
S3	E0	QM	QM	QM	QM
	E1	QM	QM	QM	A
	E2	QM	QM	ASIL A	ASIL B
	E3	QM	ASIL A	ASIL B	ASIL C
	E4	QM	ASIL B	ASIL C	ASIL D

Table 2.9. Risk graph according to [89].

In step 6 of Figure 2.5, the functional safety requirements are derived as specifications with complete independence of any particular, technological implementation; or as safety related measures which includes safety relevant properties. That is: functional safety requirements must be defined in a technology independent manner. And so must they be properly described. Furthermore, these safety-relevant properties carry the ASIL related information as well [81]. The totality of obtained functional safety requirement is regarded as the functional safety concept.

For each safety goal, at least one functional safety requirement needs to be specified; although only one functional safety requirement can cover more than one safety goal. For example, for the safety goals designated in Table 2.7 as SG1 – Deep discharge of one or more cells in the battery pack shall be prevented – and SG2 – Overcharge of one or more cells in the battery pack shall be prevented – four functional safety requirements are exemplified in Table 2.10 [2], [94].

SG1: Deep discharge of one or more cells in the battery pack shall be prevented		**ASIL**
ID	Safety requirement	C
FSR1.1	SoC of battery pack shall be determined and communicated to other items	
	Description: The system is required to track the energy flow to the cells to be able to react in case of the battery pack having a SoC that is not within the defined operational boundaries; further, if the SoC boundaries are violated this information shall be communicated to other systems of the vehicle.	
FSR1.2	If deep discharge state is detected, the current flow shall be terminated within X ms	
	Description: To protect the cells from damage and to prevent dangerous consequences from the deep discharge state like internal short circuits that can lead to thermal events and fire, the system shall shut off the current flow if a deep discharge state is detected.	
SG2: Overcharge of one or more cells in the battery pack shall be prevented		
ID	Safety requirement	
FSR2.1	Indication of overcharge shall be computed and communicated to the powertrain controller	
	Description: Indication of overcharge is required to be output by the BMS and communicated to the powertrain controller so that it knows when to stop charging. Current should not be sent to the battery if this limit has been reached	
FSR2.2	If overcharge condition is detected, current shall be interrupted within X ms	
	Description: This FSR represents a fallback safety requirement, which reacts to prevent overcharging conditions in case the charger, or inverter through regenerative braking, continues to charge the battery even when the condition of the overcharging limit has been exceeded. This FSR allows the BMS protecting for overcharge in the event where one of these external controllers, or something else within the system, malfunctions	

Table 2.10. Excerpt of a functional safety concept showing derived functional safety requirements [2], [94].

2.2.5 ASIL DECOMPOSITION

Part 9 of the standard describes the technique for how an ASIL level can be decomposed – ASIL decomposition. This means that safety functions are split up over several items or elements, resulting this in lower ASIL levels for the disassembled elements. This, in turns, makes possible reducing implementation costs, which are higher for higher ASILs. Or the introduction of redundant components with lower ASIL requirements in the specific technical solution [80]. ASIL decomposition is allowed if the resulting requirements independently satisfy the original safety requirements. Where decomposition is applied, requirements must keep the original ASIL within parenthesis, indicating this that decomposition has been implemented. In Table 2.11, ASIL decomposition is applied to the above discussed example – Deep discharge of one or more cells in the battery pack shall be prevented – on the assumption that the power electronics of the vehicle's electric motor is connected to the high voltage bus. Here, two possible measures to implement FSR 1.2 from table 4.10 are the following:

1. Deep discharge prevention, with the regulation of the requested energy to the battery pack down to zero by means of the motor's controller
2. Deep discharge prevention by isolation – i.e., opening the high voltage line from the battery pack to the controller, by means of the BMS.

SG1 **ASIL C**	**Deep discharge of one or more cells in the battery pack shall be prevented**		
FSR1.1 **ASIL C**	SoC of battery pack shall be determined and communicated to other items	**FSR1.2** **ASIL C**	If deep discharge state is detected, the current flow shall be terminated within X ms
FSR1.1, ASIL C decompose as below		**FSR1.2, ASIL C decompose as below**	
FSR1.1a **ASIL B(C)**	SoC of battery pack shall be determined from cell data and communicated to power electronics controller	**FSR1.1b** **ASIL A(C)**	Battery pack voltage shall be monitored and, in case low voltage level, it must be communicated to the BMS
FSR1.2a **ASIL B(C)**	If deep discharge state is detected, the battery pack HV DC bus shall be isolated from the HV plug within X ms	**FSR1.2b** **ASIL A(C)**	If deep discharge state is detected, the current requested from the battery pack shall be controlled to 0.0 A within X ms
Functional safety requirements allocated to BMS		**Functional safety requirements allocated to power electronics controller**	

Table 2.11. Functional safety requirement and allocation to elements with ASIL decomposition [2].

Once ASILs have been determined, the recommended measures for risk reduction are rated in the standard in dependence to the respective ASIL level and according to the following nomenclature.

- "++" highly recommendable
- "+" recommendable
- "o" no recommendation for or against the use

2.2.6 Safety life cycle and the V-Modell XT

For E/E products, a safety life cycle has already been defined in IEC 61508; i.e. the phases of product management, development, production, operation, service and decommissioning [80]. The goal is always to ensure safety management in all phases [98]. With the introduction of ISO 26262, an automotive safety life cycle with similar phases is established as well. Section 4.4.1 provides a closer look at the linkages of the individual chapters of the standard with the ISO 26262 safety life cycle, schematically represented in Figure 2.13. Parts of this life cycle model were similarly defined during software development of large software systems. In 1970, Winston W. Royce published a model describing the steps from requirement analysis to operation [99]. In any case, the individual phases are successively traversed and, if necessary, the products are improved with an iterative step back to the previous phase. It is called a waterfall model implemented with a linear approach, as it is shown in Figure 2.8.

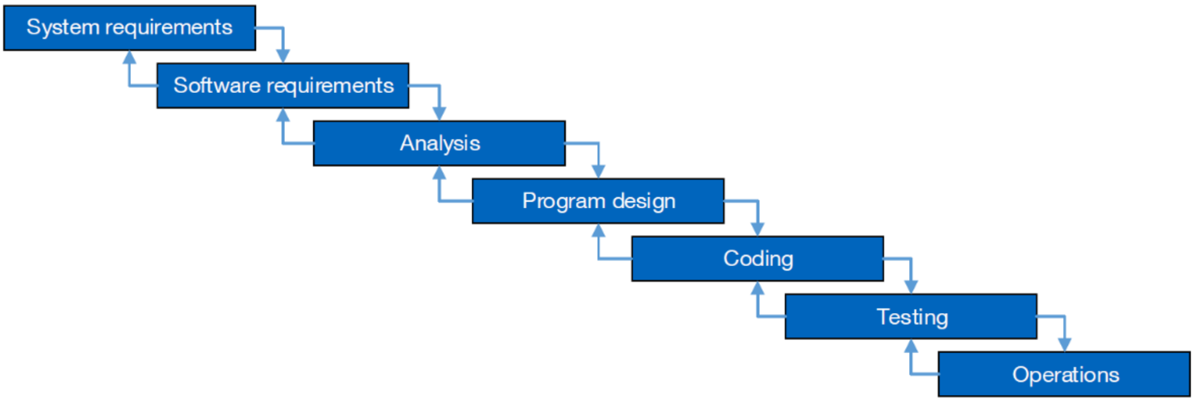


Figure 2.8. Waterfall Model according to [99].

Based on this model, the V-Modell 97 or its successor, the V-Modell XT, were developed [100], [101]. The V-Modell XT is an adaptable, flexible form of the V-model that covers the entire product life cycle [101]. Figure 2.9 shows the individual phases of the project implementation strategy. Particularly in the development strategy, the allocation of the respective phases of the left-hand side – specifications – to the right-hand side – implementation – is recognizable. Due to the phase-oriented process models, safety-relevant developments can be carried out in a quality-assured manner [80].

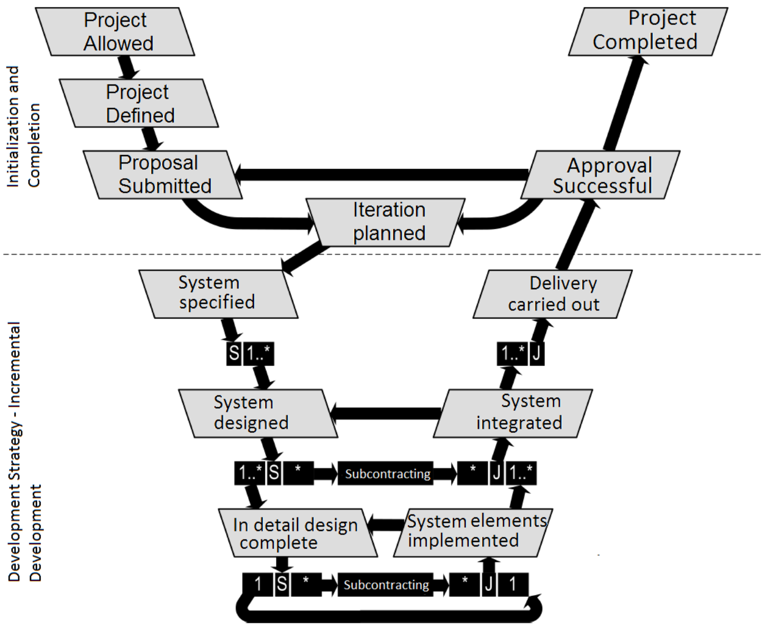


Figure 2.9. Project implementation strategy as in a V-Model XT [102], [103].

The idea of the V-model was also adopted in ISO 26262 and applied to the various levels of the system, hardware and software. According to [100], the product life cycle of a vehicle is three years in development, seven years in production and 10 to 15 years in operation and service. According the Product Safety Act [80], during this time, the product may cause no damage. In what way the development is carried out in a company is not defined in ISO 26262 [80]; but it is based on the V model.

It would also be possible [95] to use adapted Agile methods for parts of the safety-relevant development. These are approach models based on the philosophy of the so-called Agile Manifesto [104]. According to [95], a direct mapping of the Agile Manifesto and the principles to ISO 26262 does not lead to a satisfactory result. However, to carry out safety-relevant product development in an Agile manner, it must be checked whether the requirements of ISO 26262 are met by the applied processes and methods.

2.3 Structure of the Standard 2

ISO 26262 consists of 10 parts. The first 9 parts are normative and part 10 is informative. The glossary defines important terms of the standard. Parts 2, 8 and 9 describe crossed-phase activities. Parts 3 to 7 contain the requirements and recommendations for all activities of the three main phases of the safety life cycle: design, product development at the system, hardware and software levels, as well as production and execution. The individual parts are shown with clauses in Figure 2.10. The V-model with the individual assigned phases are indicated within part 4. The content of the informative part 10 is not shown in the figure.

Within the standard, parts 2 to 10 are similarly structured. Each part begins with the definition of the scope of application, followed by references within the standard. As a next step, terms, definitions, abbreviations are introduced and conditions for the conformity of the standard described, followed by the chapters with the actual content. Each subchapter is divided into: content, objectives, general, input for the clause, requirements and recommendations, as well as work results. Then, the informative appendix and the bibliography follow. In the succeeding subsections, the relevant parts are explained and a basis is established for applying the standard, from its chapter 4, to a BMS.

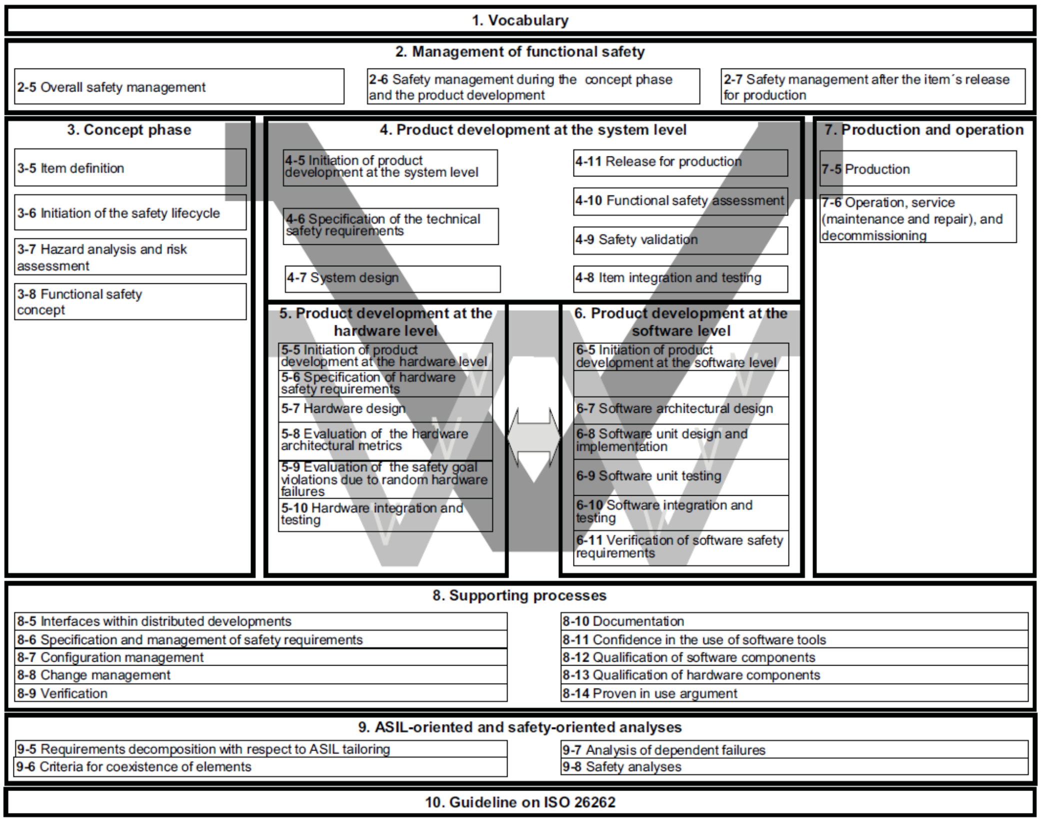


Figure 2.10. Parts and clauses – part 1 bis 9 – of ISO 26262 [80].

2.3.1 Concept phase

During the concept phase, a complete definition of the item according to ISO 26262 is carried out. Functional and non-functional requirements and interfaces with the environment of the item are to be included in the definition. The safety life cycle can then be initialized. Additionally, this imply using an impact analysis to determine whether a new development or simply a modification are dealt with. In the case of modifications to an ISO 26262 compliant product, safety-related activities can be adapted and it is not required to go through all the steps of the standard again [89], [105].

However, an impact analysis must be carried out during a modification, in which all necessary changes and their effects on functional safety need to get covered.

In the case of a new development, the hazard analysis and risk assessment described in subsection 4.2.4 must be executed. The resulting safety goals must then be generated, verified and described, as indicated in chapter 9 of [106], in order to be complete and consistent. According to [92], particular attention needs to be paid to potential common cause failures. In relation to the BMS functionalities, for instance, of significance are those manifesting as overvoltage, under-voltage, faults of the voltage regulator, EMC interference and radiation, capillary effects due to under-pressure in the housing, plug defects, altered time base of the computing units, communication faults, mechanical vibrations, moisture due to condensation and the like.

From the safety goals, resulting from the hazard analysis and risk assessment with associated ASIL levels, safety requirements are derived and summarized in the functional safety concept. These requirements must comply with [80], being clear, precise, distinct, unequivocal, verifiable, testable, maintainable, feasible, structured and comprehensible for their users.

2.3.2 Product development

The entire product development is standardized in parts 4 to 6, with part 4 playing a special roll; it describes the beginning of the development at the system level and then refers to parts 5 – hardware – and 6 – software. After development of the subsystems at hardware and software levels, the subsequent steps are executed again in part 4 of the standard – see figures 4.10 and 4.13.

2.3.3 Product development at the system level

At the beginning of product development, planning is required as a first step. Project plan, safety plan and the plan for the assessment of functional safety are to be revised and adapted to the latest state of the art. In addition, an integration and test plans as well as a validation plans are to be drawn up.

As a next step, technical solutions are specified from the generally formulated functional safety requirements of the functional safety concept. These are defined as technical safety requirements in the technical safety concept. According to [95], this strict separation is often not practiced, with transitions being rather fluid in reality. As a safety mechanism, technical safety requirements include the respective detection, the indication and the control of faults to enable the system to enter a safe state.

A special focus is on latent faults and their detection [107]. For each safety mechanism, it should also be defined how to reach the safe state, the fault tolerance time interval – see Figure 2.3 – the emergency operation interval and what measures must be taken, in order to maintain the safe state. An exemplary technical safety requirement, stated for the specific case of the BMS functional safety requirement designated as FSR 1.2a in Table 2.11 is derived and presented in Table 2.12.

The system design is then derived from the technical safety requirements. The intention here is to define an architecture which is modular and simple and has a reasonable degree of detail and accuracy. It is also defined how safety mechanisms are implemented. These should also be directly assigned to hard- and software solutions. In this step, the interfaces between hardware and software (HSI) have to be specified as well.

TSR1.2.1	The HV DC bus shall be disconnected from the battery pack poles within X ms when the SoC of the battery pack falls below Y% ASIL B (C)
Derived from	FSR1.2a
Description	If the SoC of the battery pack or individual cells falls below Y%, the HV DC bus shall be disconnected from the battery pack poles by the BMS master. The BMS master shall prevent re-connecting of the HV DC bus until charge mode is requested by the vehicle controller. Subsequent discharge shall only be permitted if a minimum SoC of the battery pack and the individual cells of Z% was reached during charging
Allocated to	BMS master
Fault diagnostic	Measurement of the DC link circuit voltage
Transition time to safe state	< X ms
Fault tolerant time interval	< Y ms
Emergency operation interval	< Z ms

Table 2.12. Example technical safety requirement for the deep discharge prevention by isolation [2].

The HSI specifications should have the following characteristics:

- The relevant operating modes of hardware devices and the relevant configuration parameters.
- The hardware features that ensure the independence between elements and support software partitioning.
- Shared and exclusive use of hardware resources.
- The access mechanism to hardware devices.
- The timing constraints defined for each service involved in the technical safety concept.

In the phase of system design, the standard requires a review of the previously planned safety activities. Deductive and inductive analysis methods can be here applied. Inductive analytical methods, such as failure mode and effect analysis (FMEA), event tree analysis (ETA), and modelling using Markov models, are highly recommended for each ASIL level. On the other hand, deductive methods, such as failure tree analysis (FTA), reliability block diagrams, cause-and-effect or Ishikawa diagrams are required for ASIL C and D [107].

2.3.4 Product development at the hardware level

From the technical safety requirements, the system design and the boundary conditions of the HSI, specific safety requirements for the hardware are derived in product development at the hardware level. If at this point security requirements are already present for the software, these should also be included. According to standard parts [108], Section 6.4.2, and [95], the hardware safety requirements have to include the following:

- Control of internal hardware failures.
- Ensuring hardware tolerance in case of failures caused by external elements.
- Compliance with the security requirements of other elements.
- Detection and signaling of internal and external failures.

According to [106] chapters 6 and 9, the hardware security requirements must be verified and documented in a verification report after their definition. Then the hardware design can be derived, typically in the form of a block diagram [95]. All elements and interfaces must be displayed. Additionally, more detailed circuit diagrams must also be created and verified afterwards. Then the evaluation of the hardware architecture metrics ensures that all possible types of failures are determined, by means of the recommended deductive and inductive analysis methods.

For ASILs C and D, it is highly recommended to calculate a fault rate for each determined simple and latent fault. For single-point faults, this is called single-point fault metric (SPFM). And for latent faults, latent-fault metric (LFM). The calculations of these key figures are described in Appendix C of [108] and explained in annex E of [108] with an example. For the two metrics, the standard defines different target values as percentages for ASIL levels B to D. These are summarized in Table 2.13.

	ASIL B	ASIL C	ASIL D
SPFM	≥90	≥97	≥99
LFM	≥60	≥80	≥90

Table 2.13. Target values for SPFM and LFM in % [108].

There are two alternative methods for evaluating violations of safety targets due to accidental hardware failures. In one case, the probabilistic metric for random hardware failures (PMHF) is used as the basis for a quantitative FTA or for Failure Mode Effects and Diagnostic Analysis (FMEDA). The standard specifies failure rates per hour for ASIL B to D. There are no requirements for ASIL A. The Failure in Time values (FIT, number of failures per 10^9 operation hours) can be used; e.g. from established industrial sources such as the Siemens standard. In the second alternative method, any cause of a safety target violation can be investigated systematically. These are classified into failure rate classes (FRC) which result in FIT values. If this method is only partially possible, a diagnostic coverage is used to determine the percentage of residual or latent faults. The target values for the determined random hardware failures are shown in Table 2.14.

ASIL B	ASIL C	ASIL D
$< 10^{-7}$	$< 10^{-7}$	$< 10^{-8}$

Table 2.14: Random hardware failure target values in h^{-1} [108].

The goals of these two metrics is to minimize failures and, if necessary, to initiate improvements to hardware design or additional security requirements [80].

Because the second method is the preferred one, it has been applied in a cell's balancing circuit for the evaluation of each single-point, random failure, in [38]. Method 2 of the standard uses an individual assessment of each circuital component in the hardware, and takes into account not only the probability of failure occurrence, but also the effectiveness of the safety mechanism. And it has been there shown that the cell's balancing circuit complies with the requirements of ISO 26262, for the satisfaction of the safety goal: Overcharge of one or more cells in the battery pack shall be prevented. This and similar safety goals are defined in [2], [94] – see Table 2.7 – for the mitigation of the hazard: Overcharge causes thermal event, also shown in Table 2.5. Actually, the activities performed in [38] are partly based on the hazard, safety goals and the safety concept found in [94]; which has been cited here in tables 4.5 and 4.10. At this point and as it can be observed in Table 2.5, ASIL C is the maximum assessment for the hazard under evaluation.

Failure rate classes are introduced in the standard to address the failure occurrence rates. And the failure rate class ranking, for a hardware part failure rate, shall be determined as follows and as stated in Table 2.15.

- The failure rate for a hardware part corresponding to failure rate class 1 (FRC1) shall be less than the target for ASIL D divided by 100 – see Table 2.14.
- Subsequently, values are always 10 times bigger for next failure rate classes (FRC2, FRC3) as observed in Table 2.15.

Failure rate class	Failure rate class value	Remark
FRC1	$<10^{-10}$ h^{-1}	Target for ASIL D ($<10^{-8}$ h^{-1}) divided by 100
FRC2	$<10^{-9}$ h^{-1}	10 times the FRC1 value
FRC3	$<10^{-8}$ h^{-1}	100 times the FRC1 value
FRCi; i>3	$<10^{-10+(i-1)}$ h^{-1}	$10^{(i-1)}$ times the FRC1 value

Table 2.15. Failure rate classes according to ISO 26262, part 5 [38], [108].

For a single-point failure leading to the violation of an ASIL C safety goal, the proper failure rate classification according to the standard is preferably FRC1; or FRC2, but with additional dedicated measures [38], [108].

In [38], research was conducted on the specific chipset BQ20Z80 from Texas Instruments and its schematic of reference [109]. According to [38], the core of the schematic is the gas gauge BQ20Z80, which computes SOC and apply safety functions. The system comprises the integrated circuit BQ2931 as an analog front end (AFE) as well as the BQ2940 as a second level, overvoltage protection. For instance, the second level, overvoltage protection senses voltage in the circuit components R4 and C4, while BQ2940 interrupts the cells current circulation with the destruction of a fuse, by means of a diode and a transistor (D4, Q4). Within this functional schematic, the AFE BQ2931, the resistor R13 and the capacitor C9 are also involved in the acquisition of the cell's voltage information.

As a specific malfunction causing overcharging – which could eventually lead to thermal runaway – an overvoltage is applied to the cells in the circuit. The following functional safety requirements are then activated:

- Indication of overcharge shall be computed and communicated to the powertrain controller and,
- If overcharge condition is detected, current shall be interrupted within X ms

For the instrumentation of the functional safety requirements in technical safety requirements, those found in [94] and later employed in [38] are next reproduced:

- Overcharge condition shall be detected within Y ms and,
- Current to the battery shall be interrupted within Z ms.

These two technical safety requirements are then allocated to the specific circuital component in the hardware, defining with this a set of safety mechanisms (SM). In this example, hypothetical safety mechanisms for overvoltage prevention are summarized in Table 2.16, as found in [38].

SM1	AFE – overcurrent protection by turning Charge/Discharge FETs off
SM2	AFE –instructed by Gas Gauge BQ20Z80 to AFE to turn Charge/Discharge FETS off
SM3	Gas Gauge (BQ20Z80) indicate implausible FET or Watchdog of AFE and blows fuse
SM4	Second level, overvoltage protection by BQ2940 blows fuse

Table 2.16. Overvoltage prevention safety mechanisms to be allocated in hardware [38].

Finding the default failure in time values for the implementation of each of the safety mechanisms in Table 2.16, the ISO 26262 standard references in Section 8.4.3 other industry standards. Among them are: IEC/TR 62380, IEC 61709, MIL HDBK 217 F notice 2, RIAC HDBK 217 Plus, UTE C80-811, NPRD 95, EN 50129:2003, Annex C, IEC 62061:2005, Annex D, RIAC FMD97 and MIL HDBK 338. For carrying out the evaluation, the failure rate values of the MIL HDBK 217 standard as well as the specifications of the component manufacturers were used in [38].

As a result of the study, the evaluation of the random hardware failure rate for the second level overvoltage protection safety mechanism and for the cell's voltage sensing mechanism, by means of the AFE BQ2931 in the schematic of reference from Texas Instruments, is shown in Table 2.17. From the table, it can be seen that the achieved failure mode coverage with respect to the violation of the safety goal – Overcharge of one or more cells in the battery pack shall be prevented – was 99%, for each considered safety related component.

Component Name	Failure rate/FIT	Safety-related component to be considered in the calculations?	Failure Mode	Failure rate distribution	Failure mode that has the potential to violate the safety goal in absence of safety mechanisms?	Safety mechanism(s) allowing to prevent the failure mode from violating the safety goal?	Failure mode coverage wrt. violation of safety goal	Residual or Single-Point Fault failure rate/FIT
Parts of the second level overvoltage protection – or one cell								
D4	3	Yes	Open	20%	Yes	SM1, SM2	99%	0,006
	3		Short	80%	No		0	0
R4	0,3	Yes	Open	90%	Yes	SM1, SM2	99%	0,0027
	0,3		Short	10%	Yes	SM1, SM2	99%	0,0003
Q4	12	Yes	Open	50%	Yes	SM1, SM2	99%	0,06
	12		Short	50%	Yes	SM1, SM2	99%	0,06
C4	4,3	Yes	Open	20%	No			0
	4,3		Short	80%	Yes	SM1, SM2	99%	0,034
IC BQ2940	0,2	Yes	All	100%	Yes	SM1, SM2	99%	0,002
Parts of the sensing of a cell voltage								
IC BQ2931	0,2	Yes	All	100%	Yes	SM3, SM4	99%	0,002
R13	0,3	Yes	Open	30%	Yes	SM4	99%	0,0009
	0,3		Short	10%	Yes	SM4	99%	0,0003
	0,3		Drift	60%	Yes	SM4	99%	0,0018
C9	4,3	Yes	Open	20%	No	SM4		0
	4,3		Short	80%	Yes	SM4	99%	0,0344

Table 2.17. Result of the evaluation of the random failure rate according to ISO 26262, part 5 [38].

Once concluding the hardware architecture design and prototyping, with the definition of its various elements, corresponding integration tests must also be defined. Depending on the assigned ASIL, different methods are listed in the standard in order to be able to derive test cases – see [108], table 10. The integration tests – ASIL A to D, induction of faults – ASIL C and D – or electrical test – ASIL A to D, are required in the standard. The induction of disturbances is also recommended in the lower ASIL levels A and B.

In [108], table 12, further hardware integration tests with their assignments to corresponding ASIL levels are presented, which are to be selected and prioritized for each case. During verification of the hardware, for example, criteria must be defined for the point of time a test is considered to have passed. Or in which verification environment it will take place: system-in-the-loop, hardware-in-the loop (HIL), software-in-the-loop (SIL), model-in-the-loop, etc. And what should be done, in consequence, if anomalies are detected [80].

2.3.5 Product development at the software level

Parallel to hardware development, software development takes place [95]. The V-model is presented in the standard as a reference phase model for software development as well. In specific cases, however, an adapted Agile approach model can also be selected, as described in subsection 4.4. At the beginning of software development, a verification plan is created, as in the case of hardware development, and existing documents are updated as required. Also at the beginning of software development, design and programming guidelines must be defined.

In the special case of model-based development, there are also guidelines for reducing systematic errors during modelling process [110]. One example is the MISRA-C; a programming standard introduced by the English Motor Industry Software Reliability Association, which is intended to support with improved code readability, reduced complexity, simple structures, and the integration of individual programming styles [102]. Further information on MISRA-C as well as on all methods required in the standard [110], which are applicable to BMS, can be found in [111].

After initiation of the product development on software level, as with the hardware, the software safety requirements are derived from the technical safety requirements [110]. Again, these must be verified and the verification documented in a report. In addition, the HSI needs to be adapted accordingly. This is followed by the development of the software architectural design.

Depending on the respective ASIL level, different notations for the software architecture are required. According to [110], table 2, an informal notation such as UML is required from ASIL Level B [95]. In order to avoid systematic faults, the standard recommends in table 3 how an architectural design should be developed. Subsequently, a safety analysis according to [112] chapter 8 must be carried out again. The mechanisms presented in table 4 can help to find faults at the software architecture level. In the case of software functions, the standard requires that freedom from interference between individual functions is ensured. For this purpose, annex D of part 6 of the standard provides information on potential types of faults which may possibly affect other functions [95]. These are for example deadlocks, time and sequence faults or memory faults [95]. After creation, the architectural design has still to be verified by the methods in table 6 of the standard.

This is followed by the actual implementation of the software units. Again, suitable methods are proposed in accordance with the ASIL levels. According to [95], for example, unnecessary complexity in the software code can be detected by metrics for software complexity, which allows to simplify the software units [95]. For that, the cyclomatic complexity V(G) according to McCabe, is recommended [95]. A control flow graph of the software unit is created and the cyclomatic complexity is calculated by means of the number of nodes and edges. The formula for individual software units is according to [95]:

$$V(G) = e - n + 2 \tag{1.3}$$

With e being the number of edges of G and n the number of vertices of G. In order to classify this measure, the risk groups and an upper limit for V (G) of 10 were defined by the OEM Software Initiative group – an association consisting of five working groups of the OEMs, Audi, BMW Group, Daimler-Chrysler, Porsche and Volkswagen, with the aim of developing common standards in the areas of standardized software modules in networks, improvement of process maturity, software tests, software tools and programming of control devices [113]. According to [95], another possibility of quantifying software complexity is the Halstead metric. In the implementation according to [110], only static analysis methods should be used. The dynamic techniques for which the code is executed are to be applied to the software tests.

As in [110], chapter 9, validation criteria must be defined in order to evaluate the results either as positive or negative, before such software module tests are performed. The results should match the HSI and software modules specifications. Furthermore, the specified functionality should be observed and for the undesired functionalities corrective actions should be proposed.

Robust behavior in regard to faults detection and fault handling mechanisms, as well as ensuring sufficient resources for function performance are specified as criteria in the standard. These tests are derived from the requirements and the planned tests strategy [80]. In addition, the software units should be analyzed by code automatic analysis tools, such as ConQAT or FxCop [102]. For automated tests, a xUnit test tool can be used [102], e.g. JUnit for Java code, or CPPUnit for C++. After successful software module tests, software integration tests are carried out, where the corresponding methods of the software module tests are used, and where external interfaces must be observed [80]. During verification by the software integration tests, software safety requirements have to be met.

In addition to the tests, the standard requires the definition of code cover metrics. This is to ensure that each branch of the software has been run at least once and all branches can be tested in appropriate combinations [80]. This code cover investigation has already been carried out in [111] with a BMS software. Like hardware, software can be tested in different environments – SIL, HIL, MIL, etc.

Once hardware and software have been integrated and verified, system integration begins. This must however be verified by various additional tests. The respective methods are presented in [107], chapter 8. After verifying the total system, the standard requires a safety validation, as described in chapter 9 of [107]. A selection of the following methods shall be carried out:

- Repeatable tests on system level.
- Various analyses, such as FMEA, FTA or ETA.
- Long-term tests.
- User tests under real conditions.
- Reviews.

Chapter 10 in [107] recalls that all documents required during the course of development have to be examined. After successful verification, a Functional Safety Assessment Report is compiled, documenting the integrity of the work results. As a final step of development the release for production follows, as regulated in chapter 11 in [107].

When developing a control prototype, selected methods of the already described development process according to ISO 26262 are used in [92]. Again a safety concept needs to be developed, including the specific safety requirements for hardware and software, which are synthesized from the hazard analysis and risk assessment, safety goals and safety requirements.

A structure FMEA is performed to verify the safety concept. Afterwards it is implemented in hardware and software. The effectiveness of the safety functions is tested by test results, for instance by a HIL test bench. Finally, a plausibility check of the results is carried out by an expert panel. The individual steps during a possible prototype development are depicted in Figure 2.11. In that way individual methods of ISO 26262 have already been implemented and can be taken into account for the development of a series product.

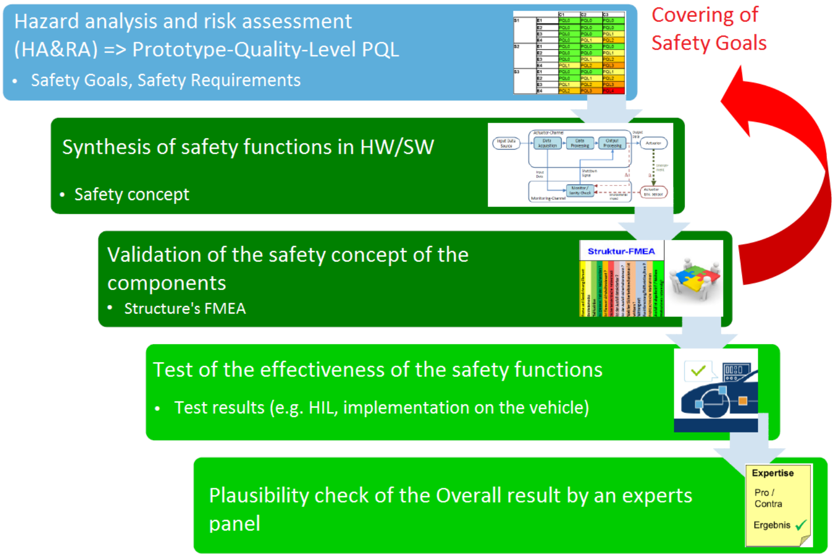


Figure 2.11. Proposed approach for the development of a control unit prototype [92].

2.3.6 Production and operation phases

Production release is followed by the production and operation phase. For production, the standard demands [114] appropriate schemes in order to be able to properly manufacture the product. This includes for example assembly instructions, tolerances and calibration requirements. If process failures occur during production, they must be analyzed and actions must be taken to correct them [95]. For the later phases of operation, maintenance and repairs, as well as decommissioning, a maintenance plan and a user manual are required, with instructions on how to deal with an error. In addition, a process that allows field observation and evaluation of the product, needs to be introduced [114].

2.4 Quality management and process models in the standard

The ISO 26262 standard is based on an established quality management system. It does not specify exactly which system should be introduced. It may be either the ISO 9001 or the ISO TS 16949 adapted for the automotive sector. In Figure 2.12, the correlation between quality management and risk reduction required for the respective ASIL is shown. Through an established quality management system and the training of the employees involved in the development activities, the existent processes in project management are in general introduced [80]. Moreover, allocation of responsibilities is carried out or resultant training requirements for employees can be identified.

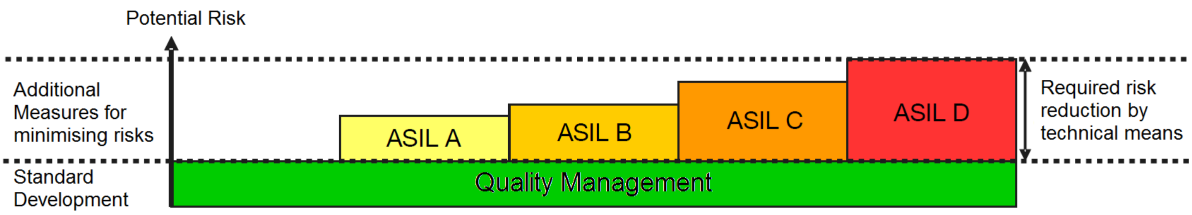


Figure 2.12. Relationship between quality management, ASIL und risk reduction according to [115].

2.4.1 Management of functional safety according to ISO 26262

In part 2 of ISO 26262, requirements and prerequisites are defined for organizations that are responsible for the safety life cycle of an automotive E/E product or are involved in it. The management of functional safety is divided into three categories: comprehensive safety management, safety management during the concept phase and product development, as well as after release for production. In addition to this rough classification, Figure 2.13 shows the links between the individual chapters throughout the entire safety life cycle in more detail.

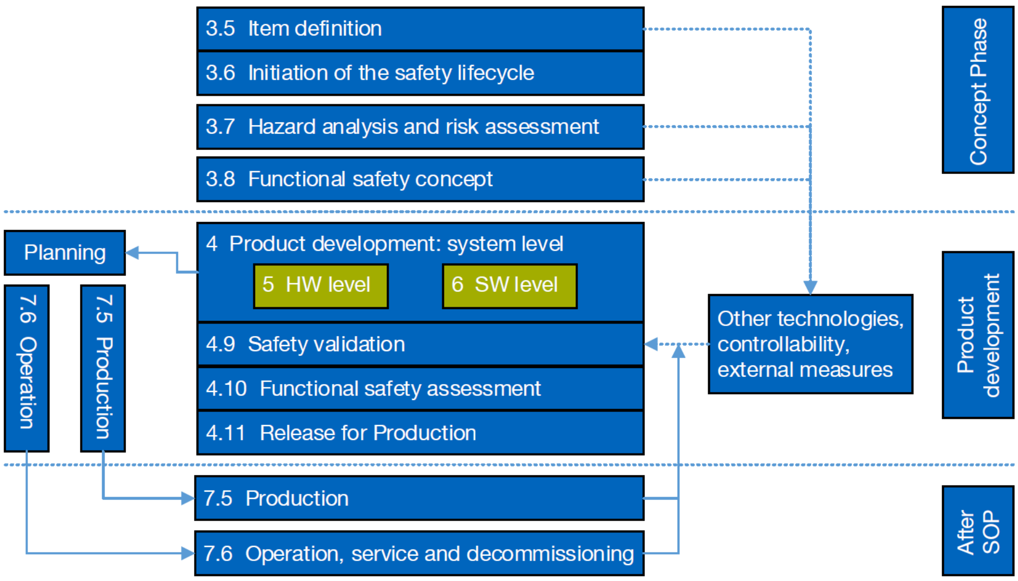


Figure 2.13. Safety life cycle according to [105] and [95].

One basis for developing in accordance to ISO 26262 consists of establishing a safety-related work culture within the company [80]. This safety culture is explicitly postulated in part 2, chapter 5, and the requirements for its development are there described. This can also be supported by the above mentioned quality management systems, as well as through an established Automotive SPICE framework; the so-called Software Process Improvement and Capability Determination, vehicle-specific IEC 15504 standard, which defines concepts for process evaluation and its application with regard to process improvement and process capability [95]. Or improvements by applying CMMI models – Capability Maturity Model Integration [95], [80]. These process improvement methods aim solely at quality management. Since ISO 26262 focuses on functional safety, its requirements are beyond the scope of these tools. The introduction of CMMI alone is not sufficient, nevertheless it supports necessary processes to develop and produce in compliance with ISO 26262 [95].

Safety culture is to be supported by appropriate rules and processes in order to enable communication of inconsistent safety-related irregularities among the participating roles. This includes the appointment of a safety manager, the allocation of role-based responsibilities and necessary prerogatives to employees involved in safety tasks [80]. Furthermore, it must be ensured that documents to be drawn up or work products of the standard are created by trained and competent employees. Thus, a competence management is as well demanded in part 2, paragraph 5.4.3.1 of the standard. As an example, in paragraph 6.4.2, the roles of the project manager and the security manager are explicitly named. In [80] further team roles are named, which do not need to be assigned necessarily to different persons. This will depend on the team and project sizes. In individual cases, it can be justified and documented whether different roles are assigned to only one employee. Roles conflicts can occur, therefore the various roles have to be planned and defined in detail at the beginning of each development.

According to [105], the safety manager is responsible for maintaining the so-called safety plan, which can be part of the project plan or a separate document. Here, processes designed to ensure functional safety are covered. They include project independent, safety-related activities and descriptions of the planning of all steps to be carried out under ISO 26262. Ensuring detailed description of all safety-related activities is of major importance. The following are to be considered: objectives, connection to other activities, responsibilities, required human resources, starting date and duration, and identification of the corresponding work result.

Functional safety audits and assessments are also part of functional safety management. These are required from an ASIL Level B. The above-mentioned measures for the creation of a safety culture may also serve as a basis for the development of prototypes. They are in line with the state of the art and support the objective of avoiding systematic faults.

2.4.2 Supporting processes and analysis methods

The eighth part of ISO 26262 describes supporting processes that are to be viewed as cross-cutting issues. This includes chapter 5 on distributed developments, which details the planning steps and processes for how a distributed development in the sense of functional safety can be organized. Part 8, chapter 6 defines how security requirements are to be generally specified and managed. The safety requirements will always be adapted to newly acquired findings from the development or verification of the individual phases.

For a detailed comprehensibility of the individual development stages and versions, the standard requires a version and configuration management. It should be planned in advance and the requirements should be adopted from the quality management. Specific requirements for software development can be defined in accordance with ISO / IEC 12207 – Systems and software engineering – Software life cycle processes. In the case of software development, configuration management can be supported with version control systems such as Git or Mercurial. An advantage arising from configuration management is according to [102] an improved overview of the current state of development.

An additional supporting process is changes management, which is introduced with the aim of ensuring control during modification processes [102]. This includes changes after assessment and certification. These amendments must be introduced stating the date, justification, exact description of the change and the configuration to be changed. The impact of this change must then be analyzed and documents adapted [106].

In chapter 9 of [106], the procedure of verification is described in general. The various points, where verification of the previous work results, are required in the standard and are referred to in this chapter. The main outcomes are a verification plan, the verification specification and a verification report.

Since the entire work results have to be recorded in form of documents, chapter 10 of the standard requires documentation management. This can be in the form of physical documents, electronic media or databases, which may also be generated automatically by supporting tools. It is explicitly pointed out that the standard aims to document information and not designing, nor appearance. Each work result should have the following elements:

- A title referring to the content
- The author and the approver
- Unambiguous identification of each different version of the document
- The change history – with the author's name, date and brief description
- The status – e.g. draft or released

Part 8, chapter 11 of the standard states whether a supported software tool is suitable for the application and whether it can be used in the corresponding ASIL level. This is for example necessary for software tools for model-based development. Chapters 12 and 13 in [106] address the qualification of hardware and software components. This qualification is intended to determine whether the respective components can be re-used in a new development in terms of functional safety.

At the end of section 8 chapter 14 in the standard, the argument of proven-in-use components is addressed. It refers, among other things, to components or software units that have already been developed before the publication of ISO 26262, or which are to be transferred from one platform to another [106]. According to [116], the argumentation of operational reliability is not always applicable. From a practical as well as a scientific point of view, Schlummer claims an alternative approach to the one defined by the standard. A possible alternative method is explained in [116].

3 INTELLECTUAL PROPERTY ON CELL MONITORING ALGORITHMS

Battery monitoring is defined as the continuous observation of the battery's states during its operation [31]. Performing monitoring of lithium-ion batteries is regarded as a complicated task due to the pronounced non-linear behavior their complex electrochemical systems exhibit, which is additionally influenced by internal and environmental conditions. The most relevant ones among these influential conditions are i) the external temperatures, ii) the charge or discharge rates or iii) SOCs. When referring to non-linear behavior, the changing of relevant battery characteristics, such as capacity or impedance as function of these conditions, are addressed.

Another important drawback in the technology of cell monitoring algorithms is the change of battery characteristics over their lifetime, which is referred to as aging of the cells. Aging of cells makes an accurate observation of the battery's states during operation even more complex.

In order to properly perform lithium-ion battery monitoring, the operational restrictions need to be observed. Operational restrictions usually define what it is called the battery's safe operating area (SOA), which is delimited by the following [31]:

- Maximum and minimum temperature
- Maximum and minimum values of voltages for each of the cells in the pack
- Maximum discharge and charging current, which in turns depend on the temperature

In addition, monitoring algorithms can also take advantages and learn from the measured signals – temperature, current and voltages – but also from the influences of the load's profiles on them. These profiles are unique for every specific battery pack, because they are dependent on the driver and the driving scenario. This will, in turn, condition a unique aging behavior for every specific battery pack if compared to the rest, what complicates the design and execution of the battery monitoring tasks even further.

Aiming to perform battery monitoring, several methodologies and techniques for SOC, SOH and SOF are widely discussed in the literature. According to [28], techniques based on electrochemical models, equivalent circuits models or statistical models are employed in order to determine impedance rise or capacity fade as main indicators of SOH and the remaining useful lifetime (RUL). In this article, on-board estimation of capacity in large lithium-ion battery packs is regarded as one of the most crucial challenges of battery monitoring. Battery temperature, discharging and charging rates and the depth of discharge (DOD) during battery operation, as well as SOC during rest periods are considered as major degradation factors [28].

The focus in this section of the study is to provide an overview of the many specific approaches to lithium-ion cells monitoring as it has been addressed in patents which belong to the public domain. Where possible, the analysis will be complemented with results found in the related literature.

3.1 PATENTS SELECTION CRITERIA

Top EV patent holders comprise a mix of automakers and battery manufacturers. The group comprises OEMs like Toyota, Nissan, Honda, General Motors, Bosch, and Panasonic as the most relevant patent holders [117].

In EV technologies, batteries, power supply systems, propulsion, and control units are the most relevant segments for patents. Other related technologies are electric elements, automotive components – gears, couplings, clutches and brakes, electric cables – and materials related to batteries, safety devices, exhaust devices, vehicle fittings and servicing. In this segment Toyota's EV portfolio is by far the largest among the top players as informed in [117]. An overview is provided in Figure 3.1. The study in [117] was carried out based on 323,960 relevant patent documents for EV technologies.

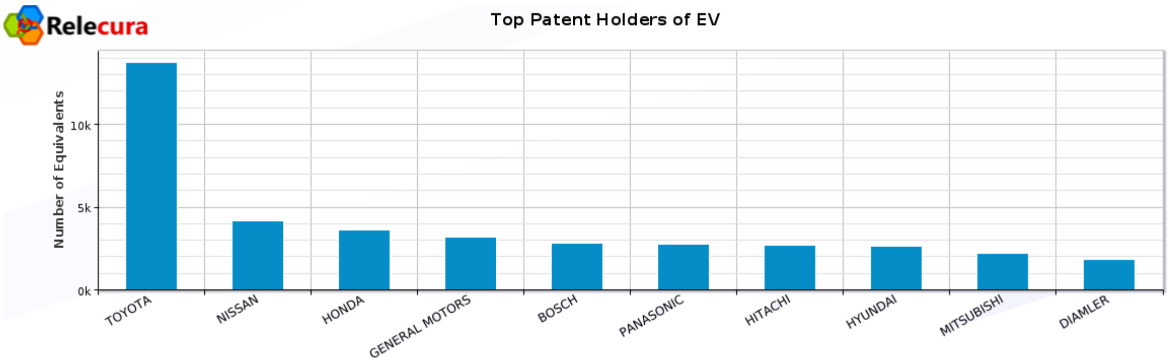


Figure 3.1. Top patents holders of EV technologies [117].

Taking into account that active markets for EVs are as well indicated by the preferred jurisdictions for patent filings, it was also found that China is the most active scenario, followed in number of applications by Japan, the U.S. and Europe, in that order. The numbers of patents applications for the technologies in the EV market segment is shown in Table 3.1.

Country Code	Country	Number of Applications
CN	China	59.428
JP	Japan	47.750
US	USA	46.916
DE	Germany	20.272
EP	Europe	19.578
KR	Korea	11.999
CA	Canada	4.323

Table 3.1. Most active markets according to the numbers of patents applications, in relation to EV technologies [117].

As with the more general segment of EV technologies, the top patent holders in the smaller sub-segment of EVs battery technologies include also OEMs like Toyota, Honda, Nissan, General Motors, Hyundai, and Bosch, as well as battery manufacturers like Panasonic, LG, Sanyo, and Samsung. This relation is also provided by [117] and in Figure 3.2. To this sub segment belongs the relevant trends battery monitoring, battery controlling and battery temperature regulation, only to mention some.

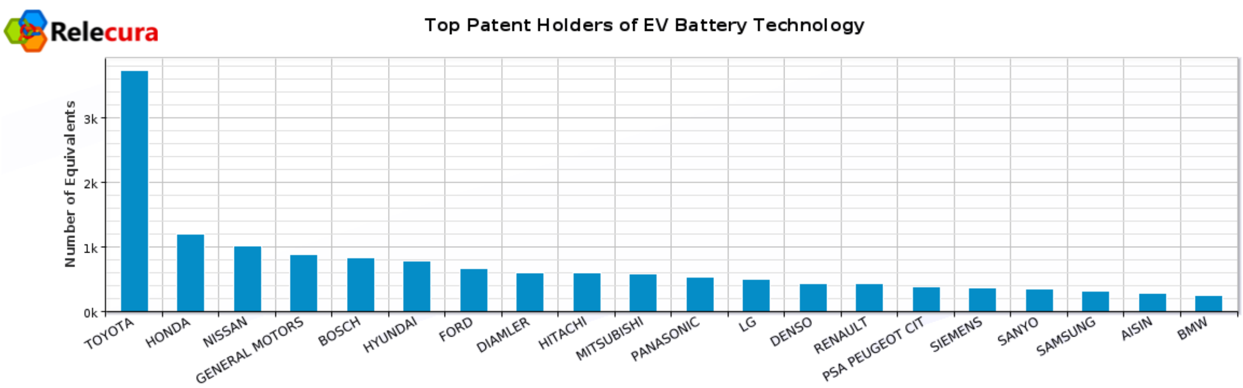


Figure 3.2. Top patents holders of battery technologies in EVs [117].

For the development of the current section of the study of the state of the art on BMS, patents from the relevant players in Figure 3.2 filled in the US and European offices were considered. The tool employed for the identification of the patents was Google Patents as in [118]. The search was configured to include the Cooperative Patent Classification codes (CPC) in Table 3.2, as representatives of the patent filling activities, in the trends of lithium ion cells monitoring in EV. The patents considered for the elaboration of this section were mainly published after 2010.

CPC codes	BMS functions and CPC codes description - battery monitoring
B60L11/1851	Battery monitoring or controlling; Arrangements of batteries, structures or switching circuits therefore
B60L11/1861	Battery monitoring or controlling; Arrangements of batteries, structures or switching circuits therefore > Monitoring or controlling state of charge (SOC)
B60L11/1864	Battery monitoring or controlling; Arrangements of batteries, structures or switching circuits therefore > Control of a battery packs, i.e. of a set of batteries with the same voltage
B60L11/1866	Battery monitoring or controlling; Arrangements of batteries, structures or switching circuits therefore > Control of a battery packs, i.e. of a set of batteries with the same voltage > Balancing the charge of multiple batteries or cells
B60L11/1868	Battery monitoring or controlling; Arrangements of batteries, structures or switching circuits therefore > Controlling two or more batteries with different voltages
B60L11/1874	Battery monitoring or controlling; Arrangements of batteries, structures or switching circuits therefore > Battery temperature regulation > by cooling
B60L11/1875	Battery monitoring or controlling; Arrangements of batteries, structures or switching circuits therefore > Battery temperature regulation > by heating
B60L11/1879	Battery monitoring or controlling; Arrangements of batteries, structures or switching circuits therefore > Adaptation of battery structures for electric vehicles
G01R31/3606	Apparatus for testing electrical condition of accumulators or electric batteries, e.g. capacity or charge condition > Monitoring, i.e. measuring or determining some variables continuously or repeatedly over time, e.g. current, voltage, temperature, state-of-charge [SoC] or state-of-health [SoH]
G01R31/3662	Apparatus for testing electrical condition of accumulators or electric batteries, e.g. capacity or charge condition > involving measuring the internal battery impedance, conductance or related variables
G01R31/3679	Apparatus for testing electrical condition of accumulators or electric batteries, e.g. capacity or charge condition > for determining battery ageing or deterioration, e.g. state-of-health (SoH), state-of-life (SoL)
G01R31/3651	Apparatus for testing electrical condition of accumulators or electric batteries, e.g. capacity or charge condition > Software aspects, e.g. battery modeling, using look-up tables, neural networks
G01R31/3655	Apparatus for testing electrical condition of accumulators or electric batteries, e.g. capacity or charge condition > the digital calculation means being combined with the battery or battery pack

Table 3.2. Battery monitoring related – Cooperative Patent Classification codes employed for patents identification [119].

3.2 Ampere-hour counting and Open Circuit Voltage-based SOC determination

The SOC in a battery can be formally defined as the relationship between the residual battery capacity in its present state (C_r) and the total battery capacity (C_{actual}) after completely charging the battery, expressed in percentage (%) [31]:

$$SOC = \frac{C_r}{C_{actual}} \cdot 100\% \tag{3.1}$$

To approach the determination of the battery SOC, several methods are proposed in literature. One of the most basic techniques is the so-called Ampere-hour or Coulomb counting, which consists of numerically calculating the battery current's time integral, representing this the variation in time of the desired magnitude with respect to an initial value [28]. The formal mathematical representation can be found in equation (3.2), where t_1 and t_2 defines the time lapse when the method is applied, η is the coulombic efficiency of the battery – for lithium-ion, η≈1 – and i(t) is the current through the battery's terminals:

$$SOC(t_2) = SOC(t_1) + \frac{1}{C_{actual}} \int_{t_1}^{t_2} \frac{\eta i(t)}{3600} dt \tag{3.2}$$

Prerequisites for the application of this simple technique are [31]:

a) An initial SOC(t_1) value has to be available.
b) Knowledge of the actual battery capacity. For the lithium-ion technologies, battery capacity is practically independent of the short-time discharge history and only significantly influenced by the current and the operating temperature at the end of discharge [31]. In general, only employing the actual battery capacity (C_{actual}) as a function of the temperature is possible, while the algorithm can frequently be updated with the latest capacity values as the battery ages.
c) Precise measurement of the battery's current in order to minimize cumulative errors when performing the numeric integration over long periods of time.
d) An additional recalibration and supportive technique – for example an OCV-based SOC estimation – in order to correct the deviation of the Coulomb counting algorithm. A known drawback, when estimating the SOC via OCV value, is the need of a considerable amount of time for the battery at a no load condition due to the voltage relaxation process [120]. Other known calibration techniques are power analysis or SOC estimation based on the calculation of the battery resistance.

In general, the Ampere-hour counting technique is considered to demand very low computing power and, when combined with other techniques for recalibration, it can perform well in BEV or HEV. It is actually the basis or a component in more complex, model based, SOC estimation techniques.

As stated above in d), the relationship between the battery OCV and the SOC is also adequate to be exploited for SOC calculations in BEV and HEV, either as a supplementary or as an independent technique. It is actually considered that necessary operational conditions for its application are met by the electric vehicles. BEV and HEV are usually driven or recharged for only some hours a day, while for a sufficient additional amount of time the battery remains in a no-load condition, enabling this an accurate identification of the SOC through the measurement of the OCV value.

Another advantage applying this technique is that changes in the OCV vs. SOC relationship are minor over the battery lifetime and, therefore, generally neglected. The shape of this relationship is a distinctive characteristic for some of the most widely used cathode chemistries: nickel-cobalt-aluminum-oxide (NCA) or nickel-manganese-cobalt (NMC), for example. For these chemistries, hysteresis is a phenomenon which can usually be neglected, being only the exception in cells with lithium-iron-phosphate (LiFePO4) cathodes or for other non-lithium-ion chemistries, such as nickel-metal-hydride (NiMH) [31].

On the other hand, when the assumptions and advantages do not apply, because the vehicle is driven and consequently recharged frequently, remaining the battery at a no-load condition only during short periods of time, or the $LiFePO_4$ chemistry has been employed, SOC recalibration through simple OCV measurements as stated above, might not yield good results. In the presence of any of these conditions, improvements to these methods need to be implemented.

3.2.1 Method and apparatus for estimating SOC of a battery – GM: US 2012/0072144 A1

Aiming to enhance the battery charging control and the vehicle power management, current SOC of the battery at any value in time (t) and temperature (T) is estimated in [121], by means of the so-called Startup SOC and Running SOC. The equation employed for this calculation is (3.3):

$$SOC = SOC_{Startup} + SOC_{Running} = f(V_{OC}(t_k), T) + \theta_{bat} \int_{t_k}^{t} i(t)dt \qquad (3.3)$$

Equation (3.3) is one possible and formal mathematical representation of the above introduced Ampere-hour counting technique, which additionally satisfies the prerequisite in a).

Here, the battery parameter θ_{bat} is a function of the batteries' coulombic efficiency (η) and the actual capacity (C_{actual}), as shown in equation (3.4).

- t_k and t are equivalents to t1 and t2 already defined for equation (3.2), but in the context observed in Figure 3.3. In the figure, t_k, tk-1 and t_{k-2} are specific time values at timepoints, when ignitions of the vehicle occur.
- $V_{OC}(t_k)$, $V_{OC}(t_{k-1})$, $V_{OC}(t_{k-2})$ are the OCV values right before ignitions are occurring
- I_f is every battery current value under a certain threshold – a condition which can be understood as a no-load condition – while I_n is any current value when the battery can be considered as loaded.

$$\theta_{bat} = \frac{\eta}{c_{actual}} \tag{3.4}$$

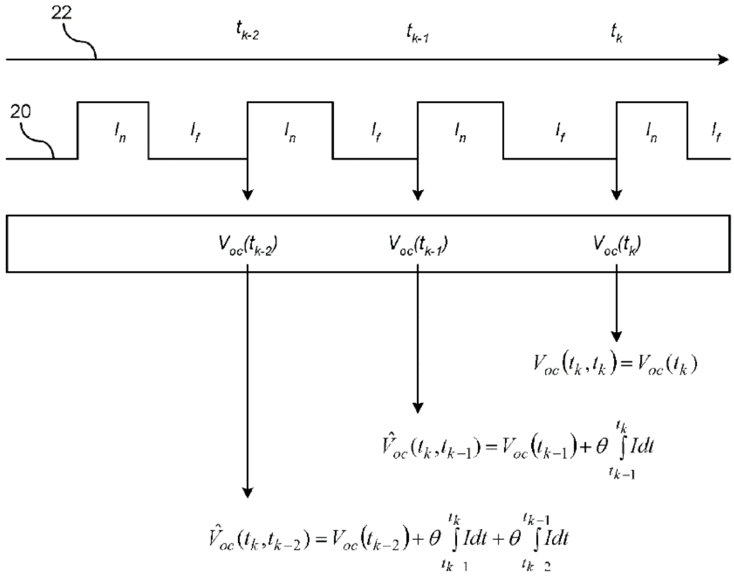


Figure 3.3. Timeline schematic illustrating time instances for determining open circuit voltages [121].

As stated in [121], properly deriving the V_{OC} is a key element in the calculation of the SOC. The method proposed also takes into account a plurality of historically estimated OCV values.

Since the amount of time at a no-load condition heavily influences the accuracy of the SOC estimation via OCV measurements, the idea lying behind this methodology consist of recursively composing an OCV value ($\widehat{V_{OC}}(t_k)$) at the last ignition time (t_k) by weighting both the OCV measured value at t_k as well as OCV compositions made at previous instants of ignitions (t_{k-1}).This is expressed in a time dependent manner in equation (3.5):

$$\widehat{V_{OC}}^{25}(t_k) = f(V_{OC}(t_k), t) = \lambda_k \widehat{V_{OC}}^{25}(t_k, t_{k-1}) + (1 - \lambda_k)\widehat{V_{OC}}^{25}(t_k, t_k) \tag{3.5}$$

Where $\widehat{V_{OC}}^{25}(t_k, t_{k-1})$ is an estimation of the OCV at time (t_k) by taking into account the OCV composition ($\widehat{V_{OC}}^{25}(t_{k-1})$) performed at the previous time of ignition (t_{k-1}), and calculated according to equation (3.6). $\widehat{V_{OC}}^{25}(t_k, t_k)$ is the OCV strictly measured at the last ignition time t_k, formally expressed in equation (3.7).

$$\widehat{V_{OC}}^{25}(t_k, t_{k-1}) = \widehat{V_{OC}}^{25}(t_{k-1}) + \widehat{\theta_{k-1}}^{25} \int_{t_{k-1}}^{t_k} i(t)dt \tag{3.6}$$

$$\widehat{V_{OC}}^{25}(t_k, t_k) = V_{OC}^{25}(t_k) \tag{3.7}$$

In equation (3.5), λ_k is the time dependent and weighting factor, calculated in accordance to equation (3.8).

$$\lambda_k = e^{-\frac{t_{off}(t_k)}{\tau}} \tag{3.8}$$

In (3.8), the term $t_{off}(t_k)$ is the time along which the battery has uninterruptedly remained at the no load condition from the ignition time t_{k-1}, and right until reaching the last ignition time t_k.

As it can be easily understood, the bigger $t_{off}(t_k)$ is, the smaller the factor λ_k will be, having in this case the strict measurement of the OCV at ignition time t_k a greater weight in the determination of the initial Startup SOC and vice versa. The shorter $t_{off}(t_k)$ is, the greater the weight of the previously composed OCV value at ignition time t_{k-1} will then show on the determination of the Startup SOC at time t_k. This in addition to a voltage value, which is proportional to the numeric current integration over the period of time between t_{k-1} and t_k.

The adjustment factor for the numeric integral of the current is $\widehat{\theta_k}$ and is recursively calculated, also in a time dependent manner, according to equations (3.9) and (3.10). In equations (3.8) and (3.10), parameters τ and τ_θ are set to be time constants:

$$\widehat{\theta_k}^{25} = \lambda_\theta \widehat{\theta_{k-1}}^{25} + (1-\lambda_\theta)\frac{V_{OC}{}^{25}(t_k) - \widehat{V_{OC}}^{25}(t_{k-1})}{\int_{t_{k-1}}^{t_k} i(t)dt} \tag{3.9}$$

$$\lambda_\theta = e^{-\frac{t_{off}(t_k)}{\tau_\theta}} \tag{3.10}$$

Due to possible temperature differences for OCV measurements at ignitions times t_k and also at previous time points, the estimation technique presented in [121] requires the normalization of the OCV measured values to perform the calculations at a defined temperature value (T) of 25°C. That is necessary in order to jointly use the OCV compositions and measurements which have been performed at different times. For this, each OCV at each ignition event is converted to an equivalent OCV based on the normalization temperature. The conversion may be performed utilizing a lookup table or an equivalent technique [121].

3.2.2 BAND SELECT STATE OF CHARGE WEIGHTED SCALING METHOD – GM: US 2012/0109556 A1

With the employment of a strategy similar in nature to that one described in the previous section, a methodology for the correction of continuous accumulation of errors – or drifting over long periods of time – of the Ampere-hour counting technique is proposed in [122]. Simultaneously, the methodology proposes a solution for the problem of a very high sensitivity to measurement errors, when some ranges of the OCV curve are employed for SOC estimation or recalibration. Actually, the methodology differentiates whether the OCV can be used as a more accurate indicator of the battery's SOC or if other indicators should be weighted heavier for the estimation. And it is suitable to be employed for any battery chemistry presenting a pronounced non-linear OCV vs. SOC characteristic.

When OCV vs. SOC characteristics are non-linear, one possible solution is to identify regions or bands in these characteristics, which might be prone to the introduction of significant errors in the estimation, because the OCV value stays nearly constant over a fairly wide range of SOC. In other words, a small OCV measurement error can introduce a huge deviation on the SOC estimation, due to the small slope of the curve around the operating point. OCV measurement errors might be introduced by the voltage sensor itself, filter gains, electronics converters, signals scaling and biasing circuits, the combination of all these or the addition of other factors. For a better understanding of the problem and its solution, [122] provides a representation of the pronounced non-linear characteristic described above, and its convenient division in regions, as it can be observed in Figure 3.4. The criteria for the definition of the limits of the region is, an approximately constant sensitivity to measurement errors within the same region.

In region 48, which represents a low state of charge, the slope is the greatest possible in comparison to all other regions in the graph. This means that, for any incremental change in SOC, there will be the largest change in the OCV value over the entire graph. Thus, in region 48, the OCV measurement could be accurately used in order to look-up the SOC, while the estimation in this region should be the best. On the other hand, in regions 54 and 56, the slope of the curve is the smallest over the entire range of SOC, meaning that here the OCV value is a very poor indicator for the SOC. In regions 54 and 56, other parameters are more suited to be used for the accurate determination of the SOC. For the instrumentation of the methodology any number of regions can be conveniently defined beforehand, depending on the shape of the curve and the battery's chemistry and pack design. Actually, many curves for different temperature values need to be measured and implemented, in order to cover the full range of operating conditions expected for the vehicle.

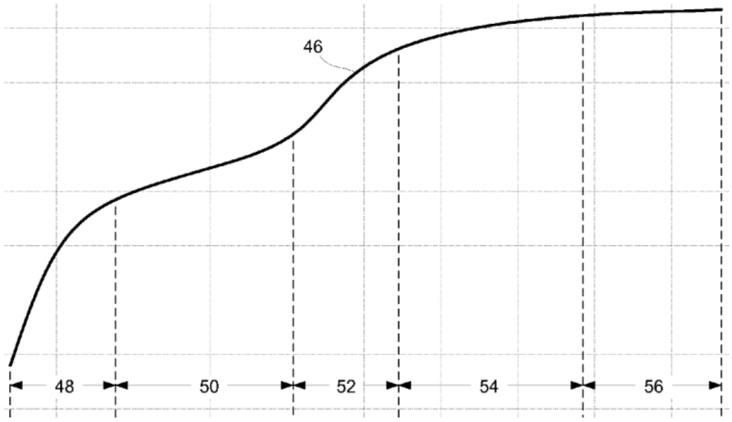


Figure 3.4. Graph of OCV vs. actual SOC in a typical electric vehicle battery pack [122].

Thus, what [122] proposes is the correction of the Ampere-hour based estimation by scaling it or refining it with an OCV- based-SOC estimation – when appropriate – by means of the weighted function in (3.11), where, among other criteria, the weight factor is established based on what region or band the battery pack operates in at any given time.

$$SOC = w \cdot SOC_{OCV} + (1 - w) \cdot SOC_{Ah} \tag{3.11}$$

In (3.11), SOC is the state of charge reported value, SOC_{OCV} is a voltage-based state of charge estimation, SOC_{Ah} is Coulomb counting-based estimation and w is a band dependent, weight factor.

According to [122], the proposed methodology is conditioned by the fulfillment of the following selective criteria:

a) The measured battery current should not exceed a certain and predefined minimum threshold value. This threshold value is established to ensure that the SOC in the battery is actually changing. In case this criterion is not met, the decision will be not to correct the SOC_{Ah} value by an OCV based estimation. This is done by setting the weight factor w to zero in equation (3.11). Of importance is that in this methodology, no explicit reference to the battery voltage relaxation time is made.
b) The computed SOC_{Ah} deviation from the SOC_{OCV} estimation should be above a certain predefined and band-dependent threshold value. In this scenario, the weighting factor w is set to zero in case of small or no deviation.

The values of minimum current thresholds and SOC_{Ah} deviation thresholds are predetermined for any particular battery pack and are different for each of the bands of the OCV-SOC characteristics. For example, for region 48 in Figure 3.4, the SOC_{Ah} deviation threshold is allowed to be small because the effect of the OCV based SOC_{OCV} calibration could be very accurate and will be applied even in case of a small deviation. That is, the confidence on the SOC_{OCV} estimation is higher. On contrary, the deviation threshold may be larger for regions 54 and 56.

Similarly, weighting factors are battery pack and band dependent as well. For example, a weighting factor near one may be used for region 48, leading to the OCV based estimation effect being dominant in the calibration of the final SOC result. On the other hand, a weighting facto near zero should be assigned to regions 54 and 56, so that the Ampere-hour based estimation will be predominant in the result. When the above criteria a) and b) are met, the weighting factor w in equation (3.11) is evaluated with non-zero values, depending on the operating temperature and determined band.

OCV measurements in conjunction with the SOC estimated value at the previous sampling time will then enable to determine the band or region from the OCV-SOC curve to be employed in the algorithm.

3.3 Ampere-hour counting and OCV-based, cells capacity and DC impedance estimation.

In general, for applications with the available energy in the battery being the most important aspect – such as in the cases of BEV and PHEV operating in charge depletion mode – the end of life (EOL) criterion for the battery pack can be defined as the decrease of its capacity (C_{actual}) to 80% of the initial value (C_{new}). In applications with the availability of power being the most important aspect, as it is the case for HEV operating in charge sustaining mode, the EOL is reached when the battery impedance (R_{actual}) has doubled. Actual battery capacity and impedance are important indicators for SOH estimation. Both SOH can be defined very similar [28], [123], as in (3.12) and (3.13):

$$SOH_C = \frac{C_{actual}}{C_{nominal}} \tag{3.12}$$

$$SOH_R = \frac{R_{actual}}{R_{nominal}} \tag{3.13}$$

The simplest way for the on-board determination of the battery capacity relies also in equation (3.2). In equation (3.14), it is calculated as the ratio between the Ampere-hours which have been charged or discharged, and the calculated difference in SOC estimated from the OCV curve (ΔSOC_{OCV}).

$$C_{actual} = \frac{\int_{t_1}^{t_2} \frac{\eta i(t)}{3600} dt}{SOC_{OCV}(t_2) - SOC_{OCV}(t_1)} \tag{3.14}$$

This technique was proposed to be implemented in an on-board set-up in [123], [124], aiming to enhance the SOC estimation and the electric power management. In [123], it is explicitly stated that, although SOC_{OCV} can usually be determined when the battery is at rest for at least a predetermined minimum period of time, it can also be determined while operating with a model based strategy as suggested in [125]–[128].

Another aspect of interest in [123] is, that the time instances t_1 and t_2, when SOC_{OCV} values are determined, can alternatively be variables, when depending on the validity of the estimation. This means that, the estimation is valid as long as the estimated capacity is constantly positive and its variation in time remains within defined limits. When the criteria are no met, sampling for new values of SOC can be done at new instances in time. Additionally, performance indices of the voltage-based SOC estimation method can be used to determine the validity, e.g. signal richness, known estimation error of the model, parameters identification method, etc.

As stated in [28], [123], it should be noticed, that ΔSOC_{OCV} must be derived from methods which are independent of the actual battery capacity value – either OCV-based or not. On the other hand, attempting the capacity determination only from the Coulomb-counting technique will always end up in a circularity of dependencies in the application of the algorithms.

3.3.1 Battery capacity estimating method and apparatus – Tesla Motors Inc.: US 8004243 B2

In [124] a methodology is proposed for the estimation of the battery capacity by means of a weighting function. In this case, also the Ampere-hour technique is employed for the estimation of the battery SOC. The update of the battery capacity value is supported by OCV-based SOC estimations as well, in this case only, when the battery has rested for a predefined amount of time. Here, the rest condition is determined, when the battery current fell – and remains – under a predefined threshold value. For EV, in which background systems are permanently in operation, this

has to be at around 2 A. As the length of time required for the battery voltage to reach the equilibrium varies with polarization, the required amount of time is a function of the temperature and it can be calculated by a look-up table or another kind of model. But even though the instrumentation of this methodology also relies in the above mentioned Coulomb-counting technique and the OCV characteristic, equation (3.14) is not directly employed in this scenario.
The Ampere-hour counting technique is constantly launched from the last time charging event of the vehicle – t=0 – until the next resting state has been reached (t_k) as determined above. In the patent, the sampling frequency for the numeric integration of the battery current is said to be 10 Hz or higher for the case of automotive applications and every one to ten seconds in other, less dynamic applications. The system permanently keeps the two last Ampere-hour values, calculated until the last two identified resting events – t_{k-1}, t_k. From these and with the non-updated, prior battery capacity value – C_{actual} – two SOC values are obtained. These are mathematically expressed in equations (3.15) and (3.16). The latest one continuously provides the information on the remaining SOC available, when the vehicle is in use:

$$SOC_{Ah-First\_time} = 1 - \frac{1}{C_{actual}} \int_0^{t_{k-1}} \frac{\eta i(t)}{3600} dt \qquad (3.15)$$

$$SOC_{Ah-Second\_time} = 1 - \frac{1}{C_{actual}} \int_0^{t_k} \frac{\eta i(t)}{3600} dt \qquad (3.16)$$

Also at time's instant t_{k-1}, t_k, OCV_{First_time} and OCV_{Second_time} are sampled. Correspondingly, $SOC_{OCV-First\_time}$ and $SOC_{OCV-Second\_time}$ values are looked-up. From them as well as from equations (3.15) and (3.16) results, differences in SOC at resting time's instants t_{k-1}, t_k are computed from equations (3.17) and (3.18):

$$\Delta SOC_{Ah} = SOC_{Ah-First\_time} - SOC_{Ah-Second\_time} \qquad (3.17)$$

$$\Delta SOC_{OCV} = SOC_{OCV-First\_time} - SOC_{OCV-Second\_time} \qquad (3.18)$$

Subsequently, it is proposed in [124] to employ the determination of a weighting value W for updating the battery capacity from the old value as follows:

$$C_{updated} = W \cdot C_{actual} \qquad (3.18)$$

Where

$$W = 100 - \left(k1 \frac{100 \cdot SOC_{Ah-Error}}{\Delta SOC_{Ah}} + k2 \frac{100 \cdot SOC_{OCV-Error}}{\Delta SOC_{OCV}} + k3 \cdot SOC_{OCV-Error-Prev}\right) \qquad (3.20)$$

In equation (3.20), constants k1, k2 and k3 are theoretically based on sensors accuracies and control loops timings, but generally tuned based in experimental application data, such as the intended use of the vehicle or how much overshoot or response time can be tolerated. For instance, in case of an EV, where consequences of overshoot are severe and there are frequent and long resting periods, the constants are set with high values to reduce the weighting factor W and the change in the battery's capacity update. The proposed values [124], for the case of an EV, are those in Table 3.3.

k	Constant's value
k1	4
k2	3
k3	8

Table 3.3. k1, k2, k3 constant's values.

The terms $SOC_{OCV-Error}$ are calculated from the OCV measurement errors in the battery [124]. In addition, this error can be expressed as well as a function of temperature and the time the battery has been allowed to rest, before performing the next capacity update. The $SOC_{OCV-Error}$ values has to be determined by taking also into account that, for example, for a cell's open circuit voltage may take up to four hours to fully relax at temperatures under 0°C, while only 10 minutes at 30°C. Therefore, if the rest time has been short and additionally temperature is cold, the employed $SOC_{OCV-Error}$ value should be higher than in more favorable conditions. Specifically, the term $SOC_{OCV-Error-Prev}$ is the value determined for the previous battery capacity update. And it is included to account for the accuracy of previous SOC_{OCV} estimations, performed at different parts of the OCV-SOC characteristic, where earlier rests took place.

In equation (3.20), the term $SOC_{Ah\text{-}Error}$ is calculated as in equation (3.21):

$$SOC_{Ah-Error} = \int (g \cdot i_{Bat} + k)dt \tag{3.21}$$

Where g is a gain error, i_{Bat} is the battery current and k is the current offset error. The integration limits are not explicitly defined in the document, although it would make sense performing the calculation, since the last charging event and until the present update at t_k.

Although it is specified that the calculations can be performed at any time as long as the system has entered the resting period, establishing some constrains might yield better results. Among them are a minimum permissible amount of time between the previous and last rest events, e.g. greater than 10 minutes for temperatures above 25°C or greater than 60 minutes during long resting periods, etc.

3.3.2 Method and apparatus for estimating battery capacity of a battery – GM: US 8612168 B2

An additional problem the patented methodology in [121], [129] addresses is the periodic update of the battery actual capacity by means of the above calculated parameter $\widehat{\theta_k}^{25}$, according to equations (3.15) and (3.16):

$$C_{actual}^{25} = C_{new}^{25} \frac{\widehat{\theta_{new}}^{25}}{\widehat{\theta_k}^{25}} = \frac{\eta_{new}^{25}}{\widehat{\theta_k}^{25}} \tag{3.15}$$

$$\widehat{\theta_{new}}^{25} = \frac{\eta_{new}^{25}}{C_{new}^{25}} \tag{3.16}$$

Where C_{actual}^{25} is the actual and normalized estimated battery capacity at 25°C, C_{new}^{25} is the normalized capacity of the new battery, $\widehat{\theta_{new}}^{25}$ is the normalized parameter of the new battery, $\widehat{\theta_k}^{25}$ is the actual normalized, estimated battery parameter as a function of the adjustment factor and η_{new}^{25} the coulombic efficiency of the new battery. For periodically updating the battery capacity, calculations must be carried out using also the values and measurements referred to the same temperature, e.g. 25 degrees.

3.3.3 Determining battery DC impedance – Tesla Motors Inc.: US 8965721 B2

In [130] a methodology for measuring cells' DC impedance as the battery ages is proposed by making use of the periodic charging routine of the EV. It is recommended to be performed from every one to four weeks when the battery is being charged – preferably overnight – and when SOC is around 60%. The methodology is applied at a controlled and desired temperature value of 35°C.

The charging process should start charging the battery pack in the desired fashion – typically for an EV by applying constant current (CC) or constant power (CP) – until the average SOC of the entire pack is the preferred one. Although suggested 60%, it is specified in the patent that the particular chosen value can be either based on the specific application and other design considerations. Also, there are some trade-offs in selecting the desired SOC for the application of the methodology. For example, between SOC values of 40% and 100%, the cell's DC impedance tends to have approximately the same value, which means that approximately the same results should be obtained over the entire range. It is also the case that various applications and usage patterns will help determining the SOC values – for example the users discharge patterns. In some cases, SOC values can be chosen higher, because some users may typically discharge their batteries only down to 70%, either because these have a very large capacity or the drivers do not drive long distances on daily bases. For this specific case, the selected value of 70% could be preferred. It should be noticed also that there are disadvantages when choosing very high SOC values, because the cells may start reaching fast the upper allowed voltage limit.

Once the preferred SOC value is reached, the charging current is cut down to zero amps and a relaxation period of at least five minutes is awaited. Controlling the temperature at the above recommended values allows a fast depolarization of the battery pack. Of course, the relaxation period may vary, or can be better adjusted, from five minutes and up, depending this on the real battery temperature value, very high charging currents – fast charging – or simply as the battery ages.

Once the battery's relaxation period has concluded, the cells' OCV values are sampled, stored and full charging current – or power – is then resumed at values at least above C/3. This charging level is considered to provide a good accuracy for the DC impedance measurement. Once sustained charging current or power values has lapsed for at least 10 seconds, the loaded cell's terminal voltages are again sampled and stored. This difference, as well as the charging current values, are employed for calculating the cell's DC impedance, according to (3.17). Additionally, the cell's estimated impedances are filtered according to the block diagram shown in Figure 3.5, aiming with this to damp the effects of noise, temperature variations and measurement inaccuracies during the described process.

$$R_{60\%}^{35°C} = \frac{\Delta V}{I_{charging}} \tag{3.17}$$

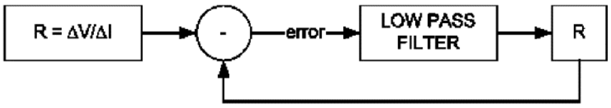


Figure 3.5. Control diagram for dampening effects of noise, temperature variation, and measurements inaccuracies during the process of cell's DC impedance estimation [130].

Once a DC impedance value is calculated, an SOH impedance degradation factor is calculated as a ratio of the measured impedance to a so-called reference impedance, which is the representation of the new battery's impedance. Ideally this is then integrated into a 3D look-up table, the battery's SOC and the temperature being used as inputs. During discharging operation, e.g. while normally driving the vehicle, the real DC impedance of the vehicle is calculated by applying the SOH degradation factor to the reference impedance, what can be then employed in the estimation of the available power and current of the battery [2], [130]. The referring equations are in (3.18) to (3.21):

$$DchILimit = \frac{V_{min} - V_{cell}}{R} \tag{3.18}$$

$$DchPLimit = DchILimit \cdot V_{min} \tag{3.19}$$

$$ChILimit = \frac{V_{max} - V_{cell}}{R} \tag{3.20}$$

$$ChPLimit = ChILimit \cdot V_{max} \tag{3.21}$$

In the equations, DchILimit is the discharge current limit, V_{min} is a value determined by the manufacturer for the particular application, V_{cell} is the actual voltage level of the battery, and R is the real-time DC impedance value, accordingly calculated. V_{min} and V_{max} are typically constant but may vary by temperature and may in consequence be used dynamically, if desired.

3.4 Model based cells monitoring. Equivalent circuits-based observers and filters

3.4.1 Dynamically adaptive method for determining the state of charge of a battery – GM: US 7768233 B2

In [131] a methodology which leverages the first-order, equivalent circuit model of a lithium-ion cell is described. The schematic representation of the equivalent circuit is provided in Figure 3.6.

In the circuit, the series resistance R models the Ohmic voltage drop in the lithium-ion cells. Capacitance C_{dl} is used to represent the internal double layer capacitance in the cell, while R_{ct} represents the charge transfer resistance. V_{OC} models the OCV vs. SOC; V_{dl} across nodes 218 and 212 is referred to as the double layer voltage, V models the voltage drops across the cells terminals and I represents the cells current.

Referring to Figure 3.6, the circuit can be characterized according to the discrete time-model shown in equations (3.22) and (3.23):

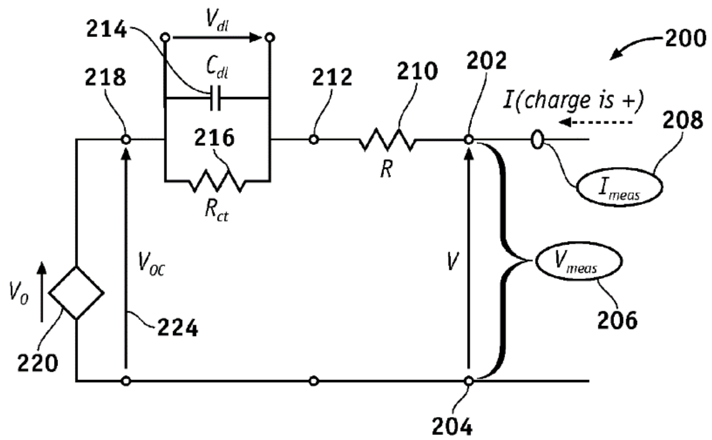


Figure 3.6. Diagram of an equivalent circuit used to model a battery system [131].

$$V(k) = V_{OC}(k) \cdot U(k) + R \cdot I(k) + V_{dl}(k) \tag{3.22}$$

$$\frac{V_{dl}(k)-V_{dl}(k-1)}{t(k)-t(k-1)} C_{dl} + \frac{V_{dl}(k-1)}{R_{ct}} = I(k-1) \tag{3.23}$$

Where

$$\Delta t(k) = t(k) - t(k-1) \tag{3.24}$$

Is the sampling time interval and U(k) is the unitary step function defined in (3.25):

$$U(k) = \begin{cases} 1; k \geq 0 \\ 0; k < 0 \end{cases} \tag{3.25}$$

Equation (3.23) was described in [131] as in equation (3.26) and later substituted in (3.22), together with (3.27), resulting in equation (3.28):

$$V_{dl}(k) = V_{dl}(k-1) - B \cdot \Delta t(k) \cdot V_{dl}(k-1) + A \cdot \Delta t(k) \cdot I(k-1) \tag{3.26}$$

From equation (3.22)

$$V_{dl}(k-1) = V(k-1) - V_{OC}(k-1) \cdot U(k-1) - R \cdot I(k-1) \tag{3.27}$$

$$V(k) - V(k-1) = -B \cdot \Delta t(k) \cdot V(k-1) + R[I(k) - I(k-1)] + (B \cdot R + A) \cdot \Delta t(k) \cdot I(k-1) + B \cdot \Delta t(k) \cdot V_{OC}(k) \cdot U(k-1) \tag{3.28}$$

Where

$$B = \frac{1}{C_{dl} \cdot R_{dl}} \tag{3.29}$$

$$A = \frac{1}{C_{dl}} \tag{3.30}$$

By making:

$$\theta_1 = -B \tag{3.31}$$

$$\theta_2 = R \tag{3.32}$$

$$\theta_3 = B \cdot R + A \tag{3.33}$$

$$\theta_4 = B \cdot V_{OC} \tag{3.34}$$

The equivalent circuit in Figure 3.6 can be modelled by equation (3.35):

$$V(k) - V(k-1) = \theta \cdot \Phi(k) \tag{3.35}$$

Where

$$\theta = [\theta_1 \quad \theta_2 \quad \theta_3 \quad \theta_4] \tag{3.36}$$

$$\Phi(k) = [\Delta t(k)V(k-1) \quad I(k) - I(k-1) \quad \Delta t(k)I(k-1) \quad \Delta t(k)U(k-1)]^T \tag{3.37}$$

Superscript T in equation (3.37) indicates the matrix transpose operation. Equation (3.35) can be expanded in a matrix form as in equation (3.38):

$$V(k) - V(k-1) = [\theta_1 \quad \theta_2 \quad \theta_3 \quad \theta_4] \times \begin{bmatrix} \Delta t(k)V(k-1) \\ I(k) - I(k-1) \\ \Delta t(k)I(k-1) \\ \Delta t(k)U(k-1) \end{bmatrix} \tag{3.38}$$

By establishing a suitable sampling time interval, periodically sampling the cells output signals V and I at sampling intervals t(k) and t(k-1), as well as iteratively storing them, the difference equation approach from (3.38) provided by [131], facilitates the ability to dynamically regress the lithium-ion cell's equivalent circuit model. The circuit's relevant parameters can be calculated from vector θ, by linearly solving the equations' system defined by (3.31) – (3.34).

Once the V_{OC} value in the equivalent circuit has been calculated, a set of look-up tables for all realistic and practical combinations of V_{OC} and temperatures can be employed for determining the cell's SOC. According to the proposed methodology, initial conditions for the parameters in vector θ can be set from values previously stored in memory, which were obtained by earlier estimations.

In addition to the model from equation (3.38), a gain vector G[4,1] is calculated in accordance with equation (3.39):

$$G = \frac{P \cdot \Phi(k)}{\lambda + \Phi^T(k) \cdot P \cdot \Phi(k)} \tag{3.39}$$

Where P is a covariance matrix for the battery parameters in vector θ, λ is a forgetting factor with $0 \leq \lambda \leq 1$ and $\Phi(k)$ is the vector from equation (3.37). The gain vector is applied to the estimation error α – see equation (3.40) – and the updated parameters vector θ_{new} is computed according to equation (3.41):

$$\alpha = V(k) - V(k-1) - \theta_{old} \cdot \Phi(k) \tag{3.40}$$

$$\theta_{new} = \theta_{old} + G \cdot \alpha \tag{3.41}$$

Accordingly, the correlation matrix P is also updated in the methodology from the relationship in equation (3.42):

$$P_{updated} = \frac{1}{\lambda} P_{old} - \frac{1}{\lambda} G \cdot \Phi^T(k) \cdot P_{old} \tag{3.42}$$

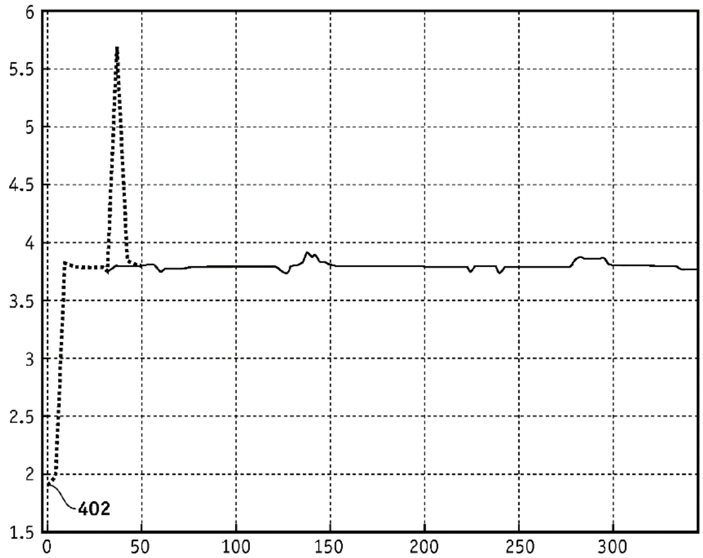


Figure 3.7. Calculated cell's voltage over time – dashed line – for an example where an incorrect initial voltage value is provided [131].

Experimental results also provided in [131] show that the adaptation of the equivalent circuit's parameters by the above described methodology yields a model with the ability of accurately reproducing the behavior of the real lithium-ion cell. Figure 3.7 is a graph that illustrates the calculated output cell's voltage over time – dashed line – superimposed to the measured real cell's voltage.

In Figure 3.7, the vertical scale indicates Volts while the horizontal scale indicates time in seconds. The experiment was performed at 40°C. For the experiment, a significantly offset initial value was intentionally entered as an initial condition. The calculated voltage ultimately settles to the measured voltage in approximately 20 seconds, showing this adaptation of the technique and its robustness to variations in the initial measurements.

It is claimed in [131], that the methodology provides a maximum terminal voltage estimation error of around 5.8 mV in a 4.0 V battery cell, which is further argued to be well below the resolution of practical vehicle voltage sensors. Moreover, it is asserted that estimation of parameter R is good under relatively high current conditions and that in addition, a good estimation of parameters A and B is achieved under relatively low current conditions, allowing this for a good characterization of the double layer effect. Furthermore, the methodology provides relatively stable and accurate results over a wide temperature range, e.g. 40°C, 25°C, -10°C.

3.4.2 Nonlinear observer for battery state of charge estimation – Ford Global Technologies. US 8706333 B2

As in [131], invention in [128] makes use of a first order equivalent circuit model of a lithium-ion battery in order to perform SOC estimation via an adaptive observer approach. The circuit model is similar to the one shown in Figure 3.6. Differences lie only at the nomenclature employed to designate the cell's double layer model – R_c and C_c for the current case – and R_r for modeling the Ohmic voltage drop. Here it is also considered the cell current to be positive when flowing out from the equivalent circuit through the positive terminal, i.e. while the cell is discharging. The mathematic model employed is equivalent but manipulated in a different and convenient way. The Ampere-hour counting technique is employed in the current methodology, also as stated as in equation (3.43). In the equation, Q represents the battery capacity and η the coulombic efficiency:

$$\frac{dSOC}{dt} = \frac{\eta}{Q} i(t) \tag{3.43}$$

Subsequently, equations (3.22) and (3.23) are reproduced but for a continuous-time system and in correspondence with the proper references and nomenclatures:

$$v_{OC}(t) = R_r \cdot i(t) + v_c(t) + v(t) \tag{3.44}$$

$$C_c \frac{dv_c(t)}{dt} + \frac{v_c(t)}{R_C} = i(t) \tag{3.45}$$

$v_c(t)$ is referred here as the double layer voltage and $v(t)$ is the cell's terminal voltage. In order to establish a continuous time model for the cell observation, equation (3.46) is added to the previous set:

$$\frac{dv_{OC}(t)}{dt} = \frac{dv_{OC}(t)}{dSOC(t)} \cdot \frac{dSOC(t)}{dt} \tag{3.46}$$

An additional necessary condition for the implementation of the current methodology is, that the OCV vs. SOC characteristics are monotonically increasing, one-to-one, first order differentiable function of SOC, so as the nonlinear term $dv_{OC}(t)/dSOC(t)$ can be determined by a nonlinear mapping to estimated $\hat{v}_{OC}(t)$ value. The implementation of this nonlinear dependence as a piece-wise linear map is suggested in [128] as stated in equation (3.47):

$$\frac{dv_{OC}(t)}{dSOC(t)} = f_1\big(v_{OC}(t)\big) = \begin{cases} l_1 & if \quad v_{OC}(t) \in [OCV_0; OCV_1] \\ l_2 & if \quad v_{OC}(t) \in [OCV_1; OCV_2] \\ \cdots & \cdots \quad \cdots \\ l_{M-1} & if \quad v_{OC}(t) \in [OCV_{M-2}; OCV_{M-1}] \\ l_M & if \quad v_{OC}(t) \in [OCV_{M-1}; OCV_M] \end{cases} \tag{3.47}$$

Evaluating equation (3.43) in (3.46) yields equation (3.48):

$$\frac{dv_{OC}(t)}{dt} = \frac{dv_{OC}(t)}{dSOC(t)} \cdot \frac{\eta}{Q} i(t) \tag{3.48}$$

By conveniently rearranging equations (3.44), (3.45) and (3.48), the continuous time equations system to be employed in this methodology by the nonlinear observer are obtained. This is shown as a matrix equation in (3.49). The output relation is found in equation (3.50):

$$\begin{bmatrix} \frac{dv_{OC}(t)}{dt} \\ \frac{dv_c(t)}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{C_c \cdot R_c} \end{bmatrix} \times \begin{bmatrix} v_{OC}(t) \\ v_c(t) \end{bmatrix} + \begin{bmatrix} -\frac{\frac{dv_{OC}}{dSOC(t)}}{Q}\eta \\ \frac{1}{C_c} \end{bmatrix} \times i(t) \tag{3.49}$$

$$v(t) = \begin{bmatrix} 1 & -1 \end{bmatrix} \times \begin{bmatrix} v_{OC}(t) \\ v_c(t) \end{bmatrix} + [-R_r] \times i(t) \tag{3.50}$$

With basis in the mathematical model defined above, the functional architecture of the proposed cell's monitoring algorithm is synthetized in Figure 3.8 a) in the form of a block diagram. As depicted in Figure 3.8 b), the cell's monitoring algorithm is initially executed in open-loop mode and it is later, in accordance with the observation of a predefined criterion, switched to the operation in closed loop mode.

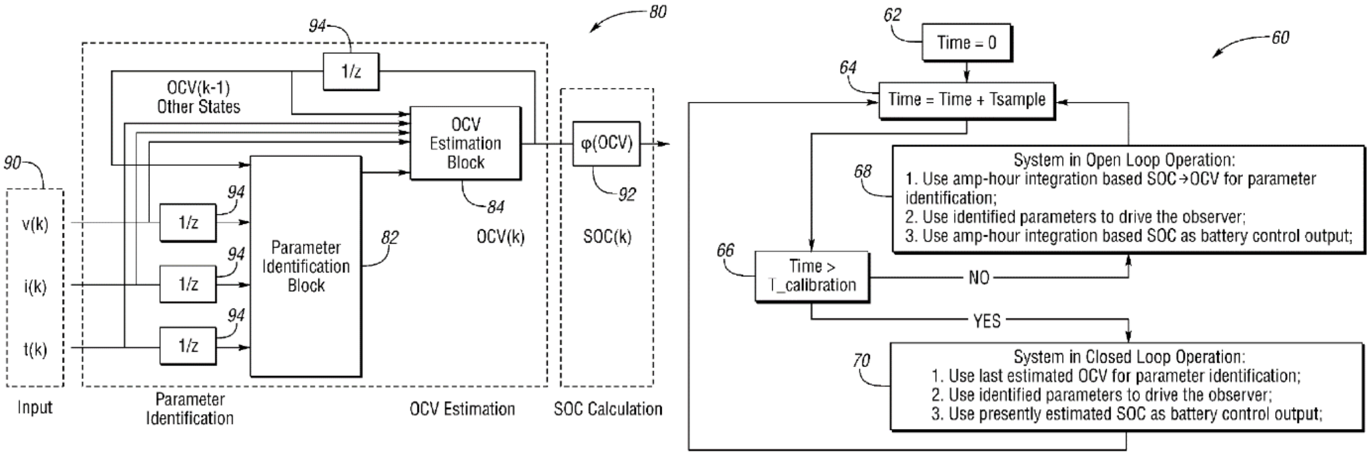


Figure 3.8. a) Cells monitoring system generic architecture. b) Block diagram illustrating the determination of open-loop vs. closed-loop operations [128].

From Figure 3.8 b), condition $Time = 0$ indicates the vehicle's key-on operation at time point when the battery has rested sufficiently, allowing this to consider the terminal voltage measurement as an accurate OCV value. This initial OCV measurement provides, in turn, the first SOC estimation and allows for further Coulomb-counting SOC and OCV estimations, by means of equation (3.2). Furthermore, and on the assumption that the Ampere-hour technique performs adequately within relatively short time's horizons, parameter identification is initially performed in open-loop mode at block 82 - see Figure 3.8 a). During open-loop operation, circuit's parameters are expected to converge to a small vicinity from the best estimated values [128].

For parameter estimations at block 82, equation (3.44) was evaluated in (3.45) yielding this further into the model in the matrix equation (3.51):

$$[v(t) - v_{OC}(t)] = \left[\frac{dv_{OC}(t)}{dt} - \frac{dv(t)}{dt} \quad -i(t) \quad -\frac{di(t)}{dt}\right] \times \begin{bmatrix} R_c \cdot C_c \\ R_r + C_c \\ R_r \cdot R_c \cdot C_c \end{bmatrix} \tag{3.51}$$

Matrix equation (3.51) can be later Laplace-transformed as in equation (3.52) and further discretized by applying the so-called Tustin or trapezoidal discretization technique, which yields equation (3.54), with T_S representing the discrete sampling time. The Tustin discretization technique basically consists of evaluating equation (3.53) in equation (3.52):

$$\frac{V_{OC}(S) - V(S)}{I(S)} = \frac{R_r \cdot R_c \cdot C_c \cdot S + R_r + R_c}{R_c \cdot C_c \cdot S + 1} \tag{3.52}$$

$$S = \frac{2}{T} \cdot \frac{Z-1}{Z+1} \tag{3.53}$$

$$\left[\frac{T_S}{2}(V_{OC}(k+1) - V(k+1) + (V_{OC}(k) - V(k)\right] =$$

$$\left[V(k+1) - V(k) - (V_{OC}(k+1) - V_{OC}(k)) \quad \frac{T_S}{2}(I(k+1) + I(k)) \quad I(k+1) + I(k)\right] \times \begin{bmatrix} R_c C_c \\ R_r + C_c \\ R_r R_c C_c \end{bmatrix} \tag{3.54}$$

The method proposed in [128] for parameter identification is the Kalman filter as part of the family of recursive parameter estimation methods for slow-varying parameter identification. In this case, equation (3.54) was reformulated as in equation (3.55), resulting in the states estimates time-update or prediction equation [132]:

$$Y(k) = \Phi^T(k) \cdot \theta(k) \tag{3.55}$$

In equation (3.55), θ(K) is the estimated parameters vector as in (3.56):

$$\theta(k) = \begin{bmatrix} R_c C_c \\ R_r + C_c \\ R_r R_c C_c \end{bmatrix} \tag{3.56}$$

Equations (3.57) to (3.60) complete the definition of the filter as found in [128], with K as the Kalman filter gain matrix, computed with equations (3.58) and (3.59), P as the process noise covariance and R_2 as the measurement noise covariance, equation (3.57) is the state estimates, measurement-update equation, while (3.6) performs the process noise covariance time update and measurement correction. R_1 is a calibration variable [128]:

$$\hat{\theta}(k+1) = \hat{\theta}(k) + K(k) \cdot (Y(k+1) - \Phi^T(k) \cdot \hat{\theta}(k)) \tag{3.57}$$

$$K(k+1) = Q(k+1) \cdot \Phi(k+1) \tag{3.58}$$

$$Q(k+1) = \frac{P(k)}{R_2 + \Phi^T(k+1) \cdot P(k) \cdot \Phi(k+1)} \tag{3.59}$$

$$P(k+1) = P(k) + R_1 - \frac{P(k) \cdot \Phi(k) \cdot \Phi^T(k) \cdot P(k)}{R_2 + \Phi^T(k+1) \cdot P(k) \cdot \Phi(k+1)} \tag{3.60}$$

By means of i) the mathematical model described in equations (3.55) to (3.60), ii) current measurements I(k) and I(k+1) at corresponding time's instants t(k) and t(k+1) on a previously defined sampling time T_S, iii) cells terminal voltages measurements V(k) and V(k+1), as well as iv) OCV – $V_{OC}(k)$ and $V_{OC}(k+1)$ – estimations performed by applying the Coulomb-counting technique, the first order equivalent circuit parameters are identified in open-loop mode.

Even though at the open-loop operational mode the SOC and estimated OCV values are provided from the Ampere-hour integration technique for battery management purpose, the non-linear observer in block 84 – Figure 3.8 a) is run and driven by the parameters being identified at block 82.

The mathematical formal definition proposed for the observer is defined in equations (3.61) and (3.62).The observer gain L – equation (3.64) – must guarantee the system's error is a stable for the entire family of lithium-ion batteries, whose behavior can be accurately modeled by equations (3.49) and (3.50). That means, making equation 3.65 a stable system with the proper selection of L_1 and L_2 values. In accordance with [128], by choosing L_1>0 and making L_2 null, the system will always result as stable under any operating condition:

$$\begin{bmatrix} \frac{d\hat{v}_{OC}(t)}{dt} \\ \frac{d\hat{v}_c(t)}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{\hat{C}_c \cdot \hat{R}_c} \end{bmatrix} \times \begin{bmatrix} \hat{v}_{OC}(t) \\ \hat{v}_c(t) \end{bmatrix} + \begin{bmatrix} -\frac{\left.\frac{dv_{OC}}{dSOC(t)}\right|_{v_{OC}=\hat{v}_{OC}(t)}}{Q}\eta \\ \frac{1}{\hat{C}_c} \end{bmatrix} \times i(t) + L \cdot (v(t) - \hat{v}(t)) \tag{3.61}$$

$$\hat{v}(t) = \begin{bmatrix} 1 & -1 \end{bmatrix} \times \begin{bmatrix} \hat{v}_{OC}(t) \\ \hat{v}_c(t) \end{bmatrix} + \begin{bmatrix} -\hat{R}_r \end{bmatrix} \times i(t) \tag{3.62}$$

$$e(t) = \begin{bmatrix} e_{v_{OC}}(t) \\ e_{v_c}(t) \end{bmatrix} = \begin{bmatrix} v_{OC}(t) \\ v_c(t) \end{bmatrix} - \begin{bmatrix} \hat{v}_{OC}(t) \\ \hat{v}_c(t) \end{bmatrix} \tag{3.63}$$

$$L = \begin{bmatrix} L_1 \\ L_2 \end{bmatrix} \tag{3.64}$$

$$\frac{de(t)}{dt} = \begin{bmatrix} -L_1 & L_1 \\ -L_2 & L_2 - \frac{1}{\hat{C}_c \cdot \hat{R}_c} \end{bmatrix} \times e(t) + \begin{bmatrix} -\frac{\frac{dv_{OC}}{dSOC(t)} - \left.\frac{dv_{OC}}{dSOC(t)}\right|_{v_{OC}=\hat{v}_{OC}(t)}}{Q}\eta \\ 0 \end{bmatrix} \times i(t) \tag{3.65}$$

As illustrated in Figure 3.8 b), the system will be running in open-loop mode, as long as a predefined condition is not satisfied. In this case, the open loop should run for a time not smaller than the T_calibration threshold. Once the elapsed time after the key-on operation overcomes the threshold, the system commutes to closed-loop mode. But this is not the only possibility for determining, whether the system should make the transition. One notable example is, that determining the length of the open-loop operation can either be timer based or can be made via input current assessment. The system could in this sense monitor the rate of change of the input current in time and prevent the system switching to closed-loop operation if certain $|di(t)/dt|$ threshold value was not overcome within a certain amount of time [128]. An additional possibility could be the assessment of the differences in $v_{OC}(t)$ over time estimations, simultaneously performed by the observer and the Ampere-hour counting technique.

In any case, once the predefined condition is satisfied, the system will switch and operate in closed-loop mode for the rest of the time, until the vehicle is again switched off. During closed-loop operational regime, OCV estimation will be further made exclusively by the observer, and SOC determined by known and temperature dependent, one-to-one nonlinear mapping. The observer will then be still driven with equivalent circuits identified parameters. The Kalman filter will continue to perform the parameters identification, but from this point in time on, v_{OC} estimated values are going to be provided by the observer.

In order to further improve the robustness and stability of the closed-loop system, identifier – Kalman filter – and observer gains can both be readjusted, so the overall closed-loop system gain is reduced, compared with its counterpart in open-loop mode. It is also explicitly claimed in the text of the patent, that the invention may be extended to any higher order equivalent circuit model where a voltage source (OCV) a resistor R_r and a number of series RC networks connected in series are employed to model a lithium-ion cell or a plurality of them.

In Figure 3.9, [128] illustrates a set of simulation results obtained through the invention.

3.4.3 State and parameter estimation for an electrochemical cell – LG Chem.: US 8103485 B2

As described in previous subsections and patents above [128], [131], the employment of dynamically adaptive methods for lithium-ion cells states estimations with basis in equivalent circuits models were addressed in various patents. Circuital models complexities do not need to be restricted to only first order but could show a better adaptation to the real behavior of the cells by means of increased orders of complexities. This is also the case for the patent under the scope in the present section [133]. The associated results of the claimed invention in [133] were published as well in [134]–[136] with a detailed procedure for the deduction of several equivalent models with diverse levels of complexities, their advantages and disadvantages, as well as the experimental results of the application of the invention itself.

In [133] a methodology which simultaneously estimates the cells states and time-varying parameter values using dual extended Kalman filtering is proposed. This methodology uses a nonlinear discrete time model of the cell that includes indicia of the dynamic system states, mainly the SOC as a model state. The circuital model in a discrete-time state-space form can be formally represented as in equations (3.66) and (3.67):

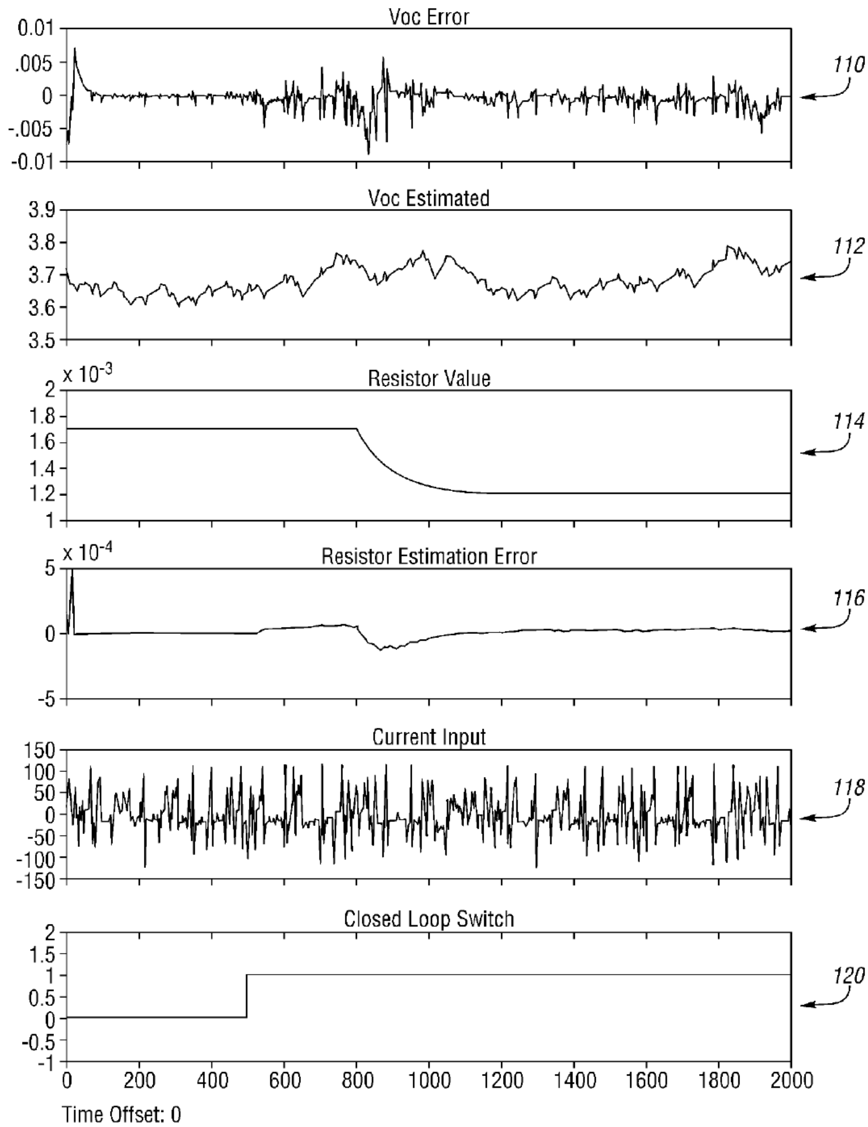


Figure 3.9. Simulation results through the proposed cells monitoring system [128].

$$x(k+1) = f(x(k), u(k), \theta(k)) + w(k) \qquad (3.66)$$

$$y(k) = g(x(k), u(k), \theta(k)) + v(k) \qquad (3.67)$$

Here, $x(k)$ is a vector comprising the system states, $\theta(k)$ is the vector comprising the set of time varying model parameters to be adapted, $u(k)$ is the system's input signal, $y(k)$ is the system output, while $w(k)$ and $v(k)$ are noisy Gaussian inputs with zero means and covariance Σ_w and Σ_v correspondingly. Functions $f(x(k),u(k),\theta(k))$ and $g(x(k),u(k),\theta(k))$ are defined by the real cell being modelled. Non-time-varying numeric values, also required by the specific model, are additionally embedded within functions f and g, although not included in $\theta(k)$.

From all the approaches presented in [135], the states vector including SOC, polarization voltage levels with respect to different time constants and hysteresis levels, is the one considered as the preferred exemplary embodiment in [133]. For this specific model, function $f(x(k),u(k),\theta(k))$ in equations (3.66) and function $g(x(k),u(k),\theta(k))$ in equation (3.67) are expanded as in equations (3.68) and (3.69). In equation (3.68), the system's input $u(k)$ includes at least the cell's current $i(k)$ and may, optionally, include the cell's temperature:

$$\begin{bmatrix} U_f(k+1) \\ h(k+1) \\ z(k+1) \end{bmatrix} = \begin{bmatrix} A_f(k) & 0 & 0 \\ 0 & e^{-\left|\frac{\eta(k)\cdot i(k)\cdot \gamma(k)\cdot \Delta t}{C(k)}\right|} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} U_f(k) \\ h(k) \\ z(k) \end{bmatrix} + \begin{bmatrix} B_f & 0 \\ 0 & 1 - e^{-\left|\frac{\eta(k)\cdot i(k)\cdot \gamma(k)\cdot \Delta t}{C(k)}\right|} \\ -\frac{\eta(k)\cdot \Delta t}{C(k)} & 0 \end{bmatrix} \times \begin{bmatrix} i(k) \\ sgn(i(k)) \end{bmatrix} \tag{3.68}$$

$$v(k) = OCV[z(k)] + G_f(k) - R(k)\cdot i(k) + M(k)\cdot h(k) \tag{3.69}$$

In equation (3.68), Δt represents the sampling period in seconds, C(k) represents the capacity of the cell in Ampere-seconds, z(k) is the SOC of cell, i(k), is the current, and η(k) is the Coulombic efficiency as stated above. The hysteresis level is captured in the single state h(K), with γ(k) as the hysteresis rate constant. In this model the polarization voltage levels are captured by several filter states, described by the n-order, diagonal matrix $A_f(k)$, which contains the time constants of the filters denoted $a(k)_1$, $a(k)_2$,…, $a(k)_n$ in its diagonal. Filter voltages $U_f(k)$ models the cell's voltage relaxation effect.

Subsequently, the output model equation (3.69) combines the state values in the system model in order to predict the cell voltage. In this equation, output y(k) equates to physically measurable cell quantities, representing the simplest case the cell voltage under load. In this equation, G_f is a vector of polarization voltage blending factors $g_1(k)$,$g_2(k)$,…, $g_n(k)$ that blend the polarization voltage states together in the output, R(k) is the cell resistance, which may have different values for discharge and charge, and M(k) is the hysteresis blending factor. Vector G may be constrained in a way that the dc-gain from i(k) to $G_f(k)$ is null.

The system parameters θ(k) are values that change slowly with time, including but not limited to cell capacity C(k), resistance R(k), polarization voltage time constants $A_f(k)$, polarization voltage blending factors $G_f(k)$, hysteresis blending factor M(k), hysteresis rate constant γ(k), efficiency η(k), and so forth. This is formally defined in [133] with equation (3.70). A mathematical model of parameter dynamics is also utilized with the form of equations (3.71) and (3.72):

$$\theta(k) = [\eta(k), C(k), a_1(k), \ldots, a_n(k), g_1(k), \ldots, g_n(k), \gamma(k), R(k), M(k), \ldots]^T \tag{3.70}$$

$$\theta(k+1) = \theta(k) + r(k) \tag{3.71}$$

$$d(k) = g(x(k), u(k), \theta(k)) + e(k) \tag{3.72}$$

Equation (3.71) defines that the parameters are essentially constant, but that they may change slowly over time, with this effect being captured by a fictitious Gaussian noise process with zero mean – denoted r(k) – with covariance Σ_r. In this case, the output of the optimum parameter dynamics is as well the cell output estimation, plus some estimation error e(k), also Gaussian, with zero mean value and covariance Σ_e.

Once the models for the system states and parameters dynamics are defined – see equations (3.66) to (3.72) – the patent suggests the application of the dual extended Kalman filtering methodology to them. The procedure should be initialized by setting the parameters and states estimated values to best guess of true values, as formally stated in equations (3.73) and (3.74). For example, an initialization of SOC might be estimated based on an OCV measurement and on previously store look-up tables:

$$\hat{\theta}_0^+ = E[\theta_0] \tag{3.73}$$

$$\hat{x}_0^+ = E[x_0] \tag{3.74}$$

In equations (3.73) and (3.74), E stands for the expected value operator. Similarly, the estimation-error covariance matrices are initialized according to equations (3.75) and (3.76):

$$\Sigma^+_{\tilde{x}_0^+} = E[(x_0 - \hat{x}_0^+)\cdot(x_0 - \hat{x}_0^+)^T] \tag{3.75}$$

$$\Sigma^+_{\tilde{\theta}_0^+} = E\left[\left(\theta_0 - \hat{\theta}_0^+\right)\cdot\left(\theta_0 - \hat{\theta}_0^+\right)^T\right] \tag{3.76}$$

Time update equations are (3.77) and (3.78) for the parameters estimation filter and its corresponding errors covariance matrix while, equivalently, the time update equations for the states and the states covariance matrix can be found in equations (3.79) and (3.80):

$$\hat{\theta}^-(k) = \hat{\theta}^+(k-1) \tag{3.77}$$

$$\Sigma^-_{\tilde{\theta}(k)} = \Sigma^+_{\tilde{\theta}(k-1)} + \Sigma_r \tag{3.78}$$

$$\hat{x}^-(k) = f(\hat{x}^+(k-1), u(k-1), \hat{\theta}^-(k)) \tag{3.79}$$

$$\Sigma^-_{\tilde{x}(k)} = A(k-1)\,\Sigma^+_{\tilde{x}(k-1)}\,A^T(k-1) + \Sigma_w \tag{3.80}$$

Where

$$A(k-1) = \left.\frac{\partial f(x(k-1), u(k-1), \hat{\theta}^-(k))}{\partial x(k-1)}\right|_{x(k-1)=\hat{x}^+(k-1)} \tag{3.81}$$

Extended Kalman filter gains are defined in equation (3.82) for the cells parameters estimation filter and in equation (3.83) for the states estimation filter:

$$L^\theta(k) = \Sigma^-_{\tilde{\theta}(k)} \cdot \left(C^\theta(k)\right)^T \left[C^\theta(k)\,\Sigma^-_{\tilde{\theta}(k)}\left(C^\theta(k)\right)^T + \Sigma_e\right]^{-1} \tag{3.82}$$

$$L^x(k) = \Sigma^-_{\tilde{x}(k)} \cdot (C^x(k))^T \left[C^x(k)\,\Sigma^-_{\tilde{x}(k)}(C^x(k))^T + \Sigma_v\right]^{-1} \tag{3.83}$$

Where $C^\theta(k)$, as stated in equation (3.84), needs a total differential expansion to be correct [136]:

$$C^\theta(k) = \left.\frac{\partial g(\hat{x}^-(k), u(k), \theta(k))}{\partial \theta(k)}\right|_{\theta(k)=\hat{\theta}^-(k)} \tag{3.84}$$

$$C^x(k) = \left.\frac{\partial g(x(k), u(k), \hat{\theta}^-(k))}{\partial x(k)}\right|_{x(k)=\hat{x}^-(k)} \tag{3.85}$$

Measurement update equations for the cells parameters estimation filter and its corresponding errors covariance matrix are described in equations (3.86) and (3.87), respectively:

$$\hat{\theta}^+(k) = \hat{\theta}^-(k) + L^\theta(k)\left[y(k) - g(\hat{x}^-(k), u(k), \hat{\theta}^-(k))\right] \tag{3.86}$$

$$\Sigma^+_{\tilde{\theta}(k)} = \left(I - L^\theta(k) \cdot C^\theta(k)\right)\Sigma^-_{\tilde{\theta}(k)} \tag{3.87}$$

Measurement update equations for the cells parameters estimation filter and its corresponding errors covariance matrix are respectively in equations (3.88) and (3.89).

$$\hat{x}^+(k) = \hat{x}^-(k) + L^x(k)\left[y(k) - g(\hat{x}^-(k), u(k), \hat{\theta}^-(k))\right] \tag{3.88}$$

$$\Sigma^+_{\tilde{x}(k)} = (I - L^x(k) \cdot C^x(k))\,\Sigma^-_{\tilde{x}(k)} \tag{3.89}$$

A block diagram representation of the proposed methodology is provided in [133] and illustrated in Figure 3.10

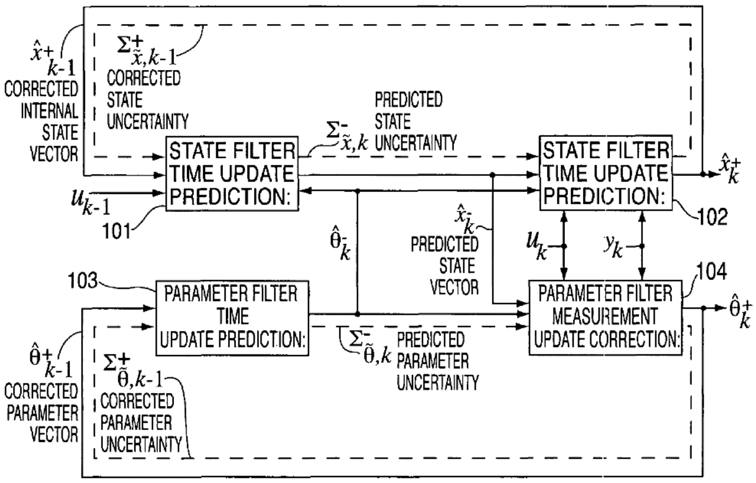


Figure 3.10. Block diagram representing the dual Kalman filter methodology applied to cells states and cells equivalent circuits' parameters estimation [133].

The dual extended Kalman filter proposed here should adapt to states and parameters values, so that the model output converges to the measured real values in the cell for the same input profile. With the approach described above, the convergence of the model states to real, physical values in the cell is not guaranteed, unless the cells phenomena are modeled very accurately. In order to guarantee convergence to the cells real states, extra steps can be taken as proposed in [133], [136]. One way can be augmenting the cell model employed for dual filtering, also to output SOC. With this aim, function g(x(k),u(k),θ(k)) in equations (3.67) and (3.69) can be augmented as in equation (3.90). Additionally, a secondary and very crude model outputting SOC estimates as a feedback signal needs to be implemented as well.

$$g\big(x(k),u(k),\theta(k)\big)=\begin{bmatrix}OCV[z(k)]+G_f(k)-R(k)\cdot i(k)+M(k)\cdot h(k)\\ z(k)\end{bmatrix} \tag{3.90}$$

The additional crude cell model from equation (3.91) can be used to provide an approximate and noisy SOC feedback signal to the dual Kalman filter:

$$\hat{z}(k)\approx OCV^{-1}[v(k)+R(k)\cdot i(k)] \tag{3.91}$$

In this case, by measuring the voltage of the cell under load, the cell current, and having knowledge of the cell resistance and the inverse OCV function, the model in (3.91) computes an approximate and noisy SOC estimate. According to [133], [136], it is expected that long term behavior in a dynamic environment is accurate, providing SOC convergence to real values in the cells.

3.5 Model based cells monitoring. Artificial Intelligence – LG Chem.: EP 1702219 B1 and US 8626679 B2

The main idea lying behind the methodologies proposed in [137], [138] consists of employing artificial neural networks (ANN) to perform SOC estimations. Estimations are based on sensed values of cell's temperature, voltages, currents and time, being these four variables the input vector to the ANN. A schematic representation of the proposal from [137] is shown in Figure 3.11. Referring to this figure, a dynamic multi-dimensional Wavelet neural network employed for SOC estimation can be instrumented with an input field or layer, a hidden layer and an output layer. To this network, $X_d(k)$ is the input vector, formally defined by equation (3.92), where i(k) stands for the cell current, V(k) for the cell voltage, T(k) is the sampled temperature, k is the number of the periodically sampled muster over time and $g_o(k)$ is the estimated SOC value.

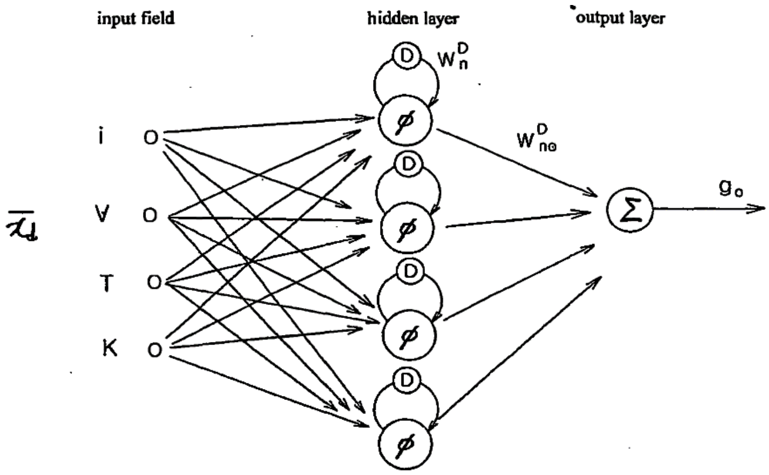


Figure 3.11. Structure of the dynamic multi-dimensional wavelet neural network used for SOC estimation [137].

$$x_d(k) = [i(k) \quad V(k) \quad T(k) \quad k] \tag{3.92}$$

As stated in [137], an arbitrary function f(x) ∊ L2(R) can be approximated as in equation (3.93), based on the Wavelet transform theory:

$$f(x) = \sum_n a_n \cdot \varphi \cdot (2^m \cdot x - n) \tag{3.93}$$

Accordingly, equation (3.94) was implemented as the dynamic multi-dimensional Wavelet neural network from Figure 3.11 as follows. Here, Φ, W_n^D and W_{no}^0 are coefficients or connection weights to be updated by training the ANN:

$$g(x) \approx \sum_n a_n \cdot \Phi \cdot (2^m \cdot x - n) \tag{3.94}$$

$$g_o(x_d(k)) \approx \sum_n W_{no}^o \cdot \Phi \cdot [\sum_d 2^m (x_d(k) - n) + W_n^D \cdot X_n(k-1)] \tag{3.95}$$

$$g_o(x_d(k)) \approx \sum_n W_{no}^o \cdot \Phi \cdot [\sum_d 2^m (x_d(k) - n) + W_n^D \cdot \Phi \cdot (\sum_d 2^m (x_d(k-1) - n) + W_n^D \cdot X_n(k-2))] \tag{3.96}$$

The approach from [138] is essentially similar to the previous one, being the only and significant difference the employment of a neuro-fuzzy algorithm for SOC estimation, instead of a dynamic multi-dimensional wavelet neural network. Here, one of the advantages is that the neuro-fuzzy algorithm is able to automatically create IF-THEN statements conforming the expert rule base, by using the learning capability of the ANN. Further advantages are based on setting the neural network size, i.e. the number of neurons to equate the number of rule bases, while using any of the fuzzy functions as an activation function. In this sense it is stated in [138], that performance of the ANN can be optimized.

The neuro-fuzzy SOC estimation algorithm from [138] has the form of equation (3.97), being Φ a fuzzy radial function, $X_d(k)$ the above defined input vector, P and W parameter and weighting factors to be updated by training, and F the estimated SOC value.

$$F = \Phi(P, X_d(k))W \tag{3.97}$$

In both cases – [137], [138] – neural networks are iteratively trained in a laboratory environment. Underlying an accurate experimental setup comprising a charger/discharger, the possibility of precisely recreating certain environmental conditions as well as different load profiles for the training, the true SOC value of the lithium-ion cell, employed as a pattern for the training of the ANN, is calculated.

Simultaneously the ANN estimates the SOC value by putting in the measured vector X_d. The estimated SOC is then compared to the measured one in the cells, by means of the charger/discharge, the Ampere-hour counting technique and the OCV calibration techniques. In every case the estimated SOC value differs from the real one in more than a predetermined threshold value, e.g. 3%, a Back Propagation (BP) learning algorithm is executed. This procedure is iteratively performed until the estimated SOC error value remains under the threshold value for every possible operating condition.

The invention stated in [138], is claimed to be broadly utilized in a field, in which the estimation of the SOC requires high precision as it is the case for hybrid electric vehicles. The invention described in [137], is described as being effectively available in the field of hybrid electric vehicles, in which the SOC of the battery has to be estimated precisely.

4 AN OVERVIEW OF THE E-MOBILITY BMS MARKET

4.1 ESTIMATED MARKET EVOLUTION AND COMPOSITION

The number of electric vehicles on the roads surpassed the symbolic threshold of one million in 2015. The global market closed at that year with cumulative values around 1.26 million and new registrations at around 550 thousands [17], [139]–[142], signifying this performance a surge of a 67,4% with respect to 2014 [140]–[142]. Also in 2015, the new registrations of electric vehicles in China outperformed, in an 82,12%, those in the US for the first time; this without taking into account that the Asiatic giant has become home to the strongest global deployment of e-scooters and exhibits, nowadays, more than 170 thousand electric buses on the streets [17]. The relevance of the global achievement in 2015 is better taken into a scope when considering that, ten years ago, electric vehicles where worldwide measured still in hundreds.

To the middle of the ongoing decade, the most dynamic EV markets where located in developed economies, all of them member states of the Electric Vehicle Initiative (EVI). Among those countries where the market shares rose above 1% were Sweden, Denmark, France, the United Kingdom and also China. The highest observed penetration happened by far in Norway and the Netherlands, where the EV market reached shares values of 23% and 10%, respectively. From these countries, Norway, Sweden and Denmark have already stated full decarbonisation goals by the middle of the current century, while Finland and Iceland targeted reductions of 80 and 50% respectively [17]. At the heart of these strategies towards the achievement of sustainable societies lies the massive electrification of the passenger's light-duty vehicles.

The worldwide leading economies have publically committed to reach the ambitious global amount of more than 12.9 million of xEVs on the road by 2020, while further goals have been set by different international organizations. Among those worth to mention are the 20 million EVs on the roads of the world by 2020, the 140 million by 2030 and the nearly 900 million by 2050 set by the EVI, which would lead to equivalent, global market shares of 1.7%, 10% and 40%. Accomplishing the targets set by the EVI should be a significant contribution in order to constrain, beneath the 2°C mark, the observed increasing trend of the global temperature [17]. Of course, whether such and further targets will in practice suffice or not can be put into question. However, what seems to be definitely irreversible is the eventual decease of the traditional ICEV.

And it is the observed aggressive development of the EVs market, together with the increasing integration of BMS in consumer electronics and renewable energy systems among other applications, a major driver for the global market of the Battery Management Systems. According to [139]–[142], the global BMS market was valued at USD 1.98 billion in 2015 and it was then estimated to hit USD 7.25 billion by 2022, yearly growing at up to 20.5%. Other sources indicated revenues for the market of USD 11.73 billion by 2025, with growths at up to 19.9% within the period 2016-2025 [143].

Only in China, driven also by the booming of its domestic EV market, the total BMS market swelled to about USD 0.65 billion in 2015 – the exchange rate that year was used – meaning this a 32,8 % of the global share. Additionally, it was then expected the Chinese portion to further soar to values between USD 2.24 and USD 2.4 billion by 2020 [140]–[142]. Other source estimated as well the weight of the Asia Pacific area excluding Japan (APEJ) to account for 29.1% of the global BMS market in 2015, followed by North America and Western Europe with a collective 40.8%. From the total, the e-mobility BMS segment shared, approximately, 14% of the market in 2015 [143].

The BMS market dynamics are complex and the stakeholders' characteristics – sizes, ages, yearly revenues, geographical positioning, core competences and interactions among them – influence its evolution. The size, age and revenues of a participant within this market may offer, for instance, an idea concerning its possibilities of investing on research and development. Or identifying whether this participant usually supplies parts to one or more well established OEMs can also be of interest, when evaluating the importance of a specific approach to the market. The relevant players within the global BMS market can be, in general, grouped as follows [140]–[142], [144], [145]:

1. Lithium-Ion cells and battery packs manufacturers: relevant players are primary cells manufacturers, many of them located and belonging to organizations headquartered in Asia. These organizations have, in many cases, expanded competences to battery packs and BMS production. Some have established long term alliances with automotive OEMs, providing complete solutions and consolidating their positions within the EV market. Others have entered via independent research and development, only to provide pre-built cell modules to be assembled later in functional battery packs.
2. BMS manufacturers: while in some cases automotive OEMs and cells manufacturers have gathered experience on the development of their own BMS solutions, and currently own a mature and reliable technology, others have seen themselves constrained by technological barriers; or perhaps by not enough research and development expenditures. For the latest, outsourcing the BMS solution has then turned out to be the more rational behavior, creating this a niche where smaller-third party BMS manufacturers have found opportunities to enter the market.
3. BMS end users: mainly, automotive, telecommunications, power grid and energy harvesting applications – either solar or wind based – as wells as consumer electronics OEMs, among others.
4. BMS chips suppliers: players falling into this group are essentially those delivering multi cell battery stack monitors; although, in general, their products portfolio is much ampler.

According to [140]–[142], the observed composition of the Chinese automotive BMS market in terms of subgroups from 1 to 3, was the following in 2015:

- BMS manufacturers: 45% of the Chinese market.
- Cells and battery packs manufacturers: 31%.
- Automotive OEMs: 24 %.

4.2 Large players in the automotive BMS market

Automotive electro-mobility regularly receives significant coverage by major media players. Topics such as electric vehicles monthly sales record [146], emerging electric vehicles automakers [147], [148] or a sufficient hardware – finally capable of level 5, autonomous driving [149] – are among the most relevant. Traditional automakers all over the world profusely advertise the advantages of their newest electric vehicles in terms of range, energy efficiency, charging times or lower pollution levels. Governments in Europe, Asia and North America strongly subside purchasing electric vehicles, reduce taxes and offer electric energy for free at public charging stations [17], in order to induce the general public to definitively abandon the internal combustion engines for a healthier future.

On the other hand, the complexities and imbrications in a functional ecosystem enabling the massive production of electric vehicles worldwide are rarely known by the man on the street. And from such a complex technological system an electric vehicle is, the big press does not spread news very often about the Battery Management Systems and its importance. Nevertheless, going through press releases, market reports and news in specialized magazines allows identifying publically known relations and strategies within the supply chain of the large automotive OEMs. Some of those relations are shown in Table 4.1, only as relevant examples [142], [145].

BMS, battery and EVs manufacturers				Production		
BMS	Battery	OEM	Model	Begin	End	Type
LG Chem., [150]	LGCPI	Hyundai Kia	Sonata	2011	2015	HEV
				2015	-	PHEV

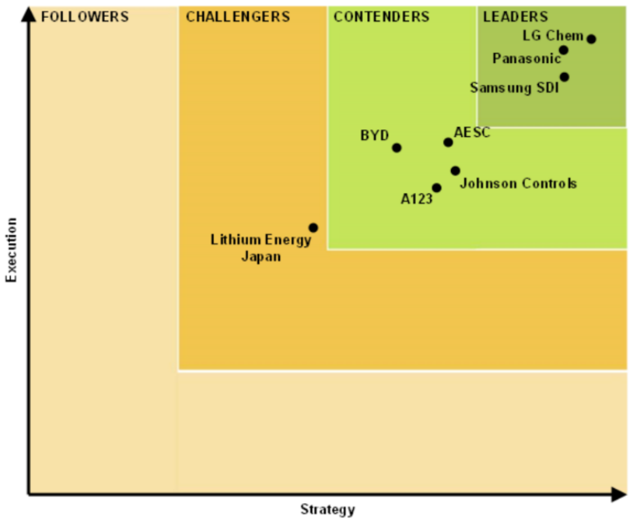
		Renault	Fluence Z.E. (1)	2013	-	BEV
			ZOE	2013	-	BEV
		GM, [151]–[155]	Chevrolet Volt (2)	2010	-	PHEV
			Chevrolet Bolt (3)	2016	-	BEV
			Cadillac ELR	2014	2016	PHEV
		Ford	Focus	2012	-	BEV
		Volvo	S60L	2015	-	PHEV
			XC90	2015	-	PHEV
	LG Chem., [156], [157]	Tesla Motors	Roadster (4)	2008	2012	BEV
DENSO	Panasonic	Toyota	Prius, [158]–[160]	1997	-	HEV
				2009	-	PHEV
			Camry hybrid	2006	-	HEV
	-		Highlander (5)	2006	-	HEV
	-		Lexus LS, [161]	2007	-	HEV
	-		Lexus GS, [162]	2006	-	HEV
	-		Daihatsu Mebius	2013	-	HEV
	-		Lexus RX	2005	-	HEV
BYD			F3DM	2008	2013	HEV
			Qin	2013	-	PHEV
			E6	2009	-	BEV
Preh GmbH	SB LiMotive	BMW, [163]–[167]	Active E	2011	2012	BEV
			i3	2013	-	BEV
	-		i8	2014	-	PHEV
Tesla Motors	Panasonic	Toyota, [168]	RAV4 EV (6)	2012	2014	BEV
		Daimler, [169]	Smart fortwo	2009	2012	BEV
		Tesla Motors	Model S	2012	-	BEV
Continental AG	Saft	Daimler, [170]	Mercedes S400 (7)	2005	2013	HEV
	Sk Innovation	Renault, [171]	Scenic Hybrid Assist	2016	-	HEV
Honda	Toshiba	Honda	Fit or Jazz	2012	2015	BEV
	Blue Energy		Accord	2013	-	PHEV
Hyundai Kefico	Hyundai + LG Chem	Hyundai Kia, [172]	ix35	2005	-	FCEV
Calsonic Kansei	AESC	Nissan	Leaf	2010	-	BEV
Epower Electronics	Guoxuan High-tech Power Energy	JAC	iEV4	2010	-	BEV
Hitachi	AESC	Nissan	Pathfinder	2013	2014	HEV
Mitsubishi	LEJ	Mitsubishi	i-MiEV (8)	2009	-	BEV

Table 4.1. Automotive OEMs and the BMS supply chain [142], [145].

(1) Also sold as Samsung SM3 Z.E. or Dongfeng Fenguno E300.
(2) Also sold as Holden Volt, Opel Ampera or Vauxhall Ampera.
(3) Also sold as Opel Ampera-e.
(4) Third battery pack replacement for the Roadster.
(5) Also sold as Kluger.
(6) Second Generation.
(7) Also known as BlueHYBRID.
(8) Also known as Citroën C-Zero or Peugeot iOn.

4.2.1 LG Chem: a very important BMS supplier

As it can be observed in Table 4.1, LG Chem manufactures not only lithium-ion cells but the complete solution of energy storage systems in the automotive industry. According to Navigant Research – formerly Pike Research – LG Chem has established itself as a leader in the markets of lithium-ion batteries for grid storage systems as well as transportation. For comparison, the players were rated on 12 criteria: vision; go-to market strategy; partners; production strategy; technology; geographic reach; sales, marketing, and distribution; product performance; product quality and reliability; product portfolio; pricing; and staying power. And the Korean company has made other renowned contenders such as Panasonic, Samsung SDI, Kokam, A123, Hitachi, Saft or BYD to lag behind, in terms of strategy and execution. Graphical representations and qualitative evaluations are offered by LG Chem and Navigant Research, in figures 1.1 a) and b) [173]–[176].



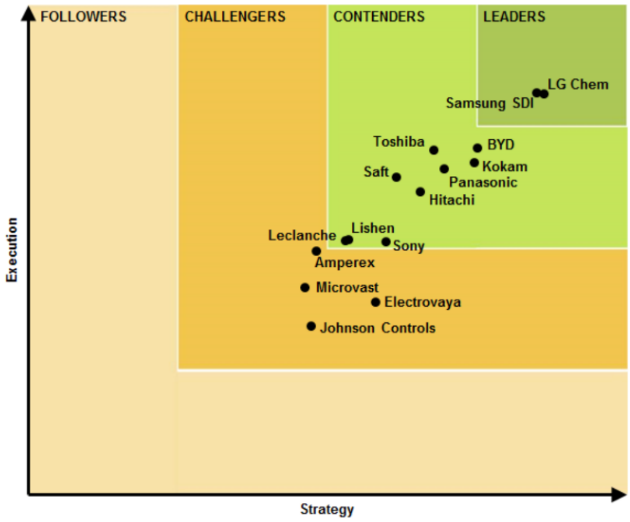


Figure 4.1. Leading position of LG Chem in terms of strategy and execution, according to Navigant Research: a) Light-duty electric vehicle battery market [150], [176], b) Lithium-Ion Grid Storage market [175].

Also in terms of the market share, analysts from Lux Research have estimated scenarios by 2020 where LG Chem could overtake the favorable and dominant position Panasonic currently owns. One of the projections made by Lux Research has been published by LG Chem [150] and can be seen in Figure 4.2. In this figure, two main groups can be recognized over the entire projection period. Right now, Panasonic rules the battery landscape for plug-in electric vehicles with about 40 % of the market, by virtue of its long-term, large-volume supply relationship with Tesla Motors; a single deal with a niche OEM which outperforms more than a dozen of others that LG Chem and Samsung SDI have established with larger OEMs. Closely following and sharing about 20 % of the market, LG Chem performs already as the second biggest player which could win the game in the long run.

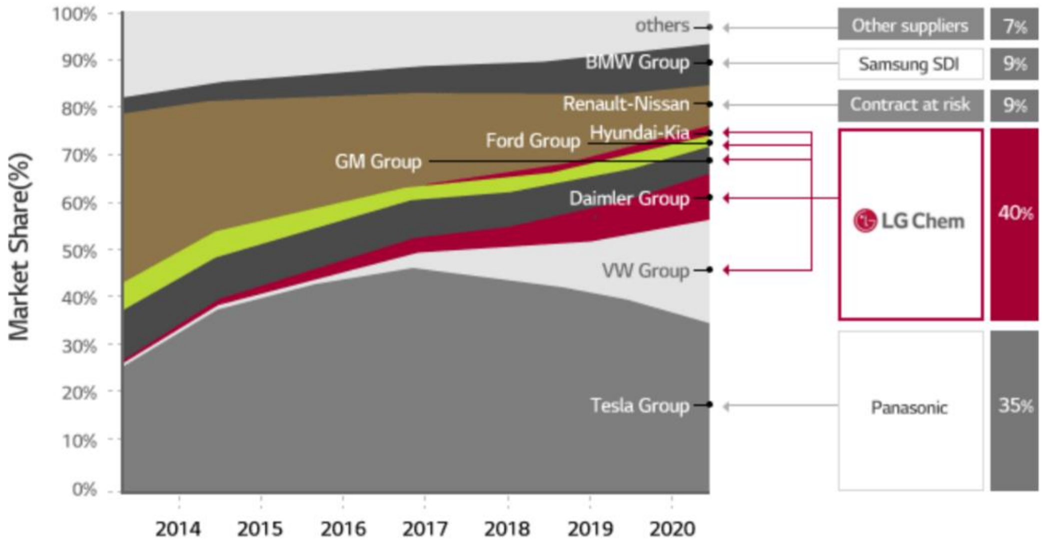


Figure 4.2. Lithium-ion batteries market share in e-mobility [150].

LG Chem currently provides its complete energy storage system solution to many traditional automakers. Even for the Tesla Motors' Roadster, third generation, battery pack replacement [156], [157]. The current and future trend shown in Figure 4.2 could be an approximated indicator of the predominance of this big player in the automotive BMS market. As it can be observed in Table 4.1, as well as in [150], LG Chem provides energy storage solutions for a big group of OEMs and many kinds of electric, terrestrial means of transportation.

4.2.2 48 V-mild hybrid electric powertrains: Delphi Automotive PLC and Continental AG

In comparison to LG Chem, a more limited approach to the e-mobility segment of the BMS market is the one shown by this two specific actors within the traditional supply chain of known OEMs [177]–[179]. And such an approach seems to be well supported by estimations, this time provided by IHS Automotive. IHS Automotive projects that, by 2025, as many as 13 million vehicles will be 48 V-mild hybrid, up from a small 63 thousand units on the roads in 2015 [180]; according to [181], around 11 million or the 10 percent of the vehicles produced in 2025 will be mild hybrid, 48 V-powered, becoming those the best value solution.

And with future regulations of 95g CO2/km in Europe and 54.5MPG in the United States – by 2025 and 2021 respectively – there is and will be a huge pressure on the automakers. In consequence, the industry has optimized and further downsized the internal combustion engines. By means of the electrification of the power train, automakers get close to those preferred emission targets, while improving the fuel economy.

In this scenario, Delphi Automotive PLC claim that its 48 V technology may serve as a logical bridge, from the 12 V, star-stop diesel engines already on the road, to full hybrids; this without the need of completely overhauling the vehicles platforms at the manufacturing sites, which always needs extra time and money. The main idea is simply packing the 48 V system in the same vehicle and powertrain, together with few more added components. This can improve performance with 25 % of additional torque when compared to a 12 V system, while delivering 50 to 70 % of the fuel savings of a full hybrid, at only 30 % of its costs [54], [181]–[184]. Applying this strategy for the next decade should improve the full hybrid vehicles' market acceptance, while the path to massive and full electrification of the passenger's light-duty vehicles is getting paved.

For Continental AG, the complete hybridization of the drive train of smaller cars at 48 V before 2025 is doable, especially for the movers with autonomous driving technology. And even though some of their specialists also consider, that for luxury and bigger cars full electrification will be possible between 2025 and 2030, 48 V will still be the bridge technology with high volume production, for the next 25 years [185].

In this sense, Continental AG has publically stated that the volume production of their 48 V mild hybrid drive has begun and it is massively introduced in the Scenic Hybrid Assist by the French automaker Renault, from the end of 2016 [171]. Also by mid of 2016, Delphi Automotive PLC communicated to the press, that sub brands of two important automakers will incorporate their 48 V solution by 2018 [182]–[184], [186] but so far has declined to name the specific models. Media has later speculated and pulled together in the publications, names such as the SQ7 crossover from Audi and Bentley's new Bentayga SUV, both luxury brands from the Volkswagen AG group, Honda Civic or BMW [182]–[184], [186]–[188].

4.2.3 BMW outsources BMS production to Preh GmbH

Another important contributor to the automotive BMS market, from those recognized as traditional automotive OEM part suppliers, is the Preh Group – or Preh GmbH; originally a German company which became part of the Ningbo-based, Chinese group, Joyson Electronic Corp in 2012. [189], [190]. Among the technological solutions Preh GmbH provides the OEMs with are interior control systems – also named as center stacks – or the Climate Electronic Control Units for sub brands from General Motors, Ford and the BMW and VW groups [191]–[198].

The Preh Group has moved some steps forward in the future-oriented market for electric and hybrid vehicles as well, in this case together with the BMW group. Models like the pure electric ones BMW i3 and ActiveE or the plug-in hybrids BMW i8 and ActiveHybrid 5, serially incorporate Preh's Battery Management Systems for the reliable operation of their 320 V-battery packs. As of 2015, the latest news mentioned also the introduction of a 48 V Battery Management System, which is probably expected to be incorporated in serially produced, mild hybrid BMW models [140]–[142], [144], [145], [163]–[167].

4.3 Minor third party BMS manufacturers for the electro-mobility

The need for the electro-mobility has uncovered a plurality of niches for start-ups willing to join this promising market, such as Tesla Motors, Lucid Air and Faraday Future, but not only. The boom of the electric cars create business opportunities for traditional automakers with solid positions, as well as for those not that prosperous which, although having experienced the success of some of their very popular sub brands, were not able to survive economic difficulties, even bankruptcy.

While some of their models still enjoy the fame fairly gained over many years, the OEMs have been resold and reorganized, creating sometimes own dedicated, production subsidiaries for the satisfaction of the technological requirements of the electro-mobility.

4.3.1 Ventec-intelligent Battery Management System and Venturi Automobiles

One example of interest is that one of Venturi Automobiles. This Monegasque-based, multinational automotive manufacturer was founded in 1984, and used to design, build and sell luxury vehicles. Gildo Pallanca Pastor, purchased Venturi Automobiles in 2001 after bankruptcy, and decided to focus on electric powered engines for his vehicles. Subsequently, Venturi Automobiles expanded with the purchase, in 2009, of the French Voxan: a motorcycles manufacturer. Voxan immediately ceased its conventional ICE motorcycles production line and announced the creation of an electric prototype – the WATTMAN. In 2011 Venturi Automobiles further created a division in Ohio, USA, as a research and development center which maintains a close working relationship with the Center for Automotive Research [199], [200].

Gildo Pallanca Pastor is also co-founder and Chairman of the Board of Directors of Ventec-Intelligent Battery Management System [201]–[203] or Ventec-iBMS – sometimes also named as Ventec SAS. With headquarters in Merignac, France, Ventec – iBMS is a small company with exclusive dedication to the production of Battery Management Systems – its iBMS. The products the company offers comprise 5 different types of BMS, intended for different applications. Among them are electric tools, robots, lawn mowers, solar panels, but also traction in passengers e-mobility products, such as e-bikes, e-scooters, tricycles and small electric vehicles, either hybrid or fully electric [71], [204], [205].

Ventec – iBMS main customers are players in the French battery industry for electric vehicles. Because the company works as a supplier in a Business to Business (B2B) scheme, it is not usual getting to know the receptors of most of its products. It is anyway possible to find a few customer names in news or press releases, among them the French fuel cell manufacturers Pragma Industries in Biarritz, France, the European electric bikes leader Cycleeurope and the manufacturer of the sun-powered electric lights Sunna Design in Blanquefort, also France [201], [206], [207].

Additionally, the solutions developed by Ventec are commonly found in the electronic boxes of electric vehicles of all kinds, from racing karts to sports cars such as the America or Fetish, from Venturi Automobiles [201], [208].

4.3.2 Frazer-Nash Energy Systems

A second example is the one of the Frazer-Nash group of companies. First founded in 1922 as sport car manufacturer, Frazer-Nash worked closely together with other traditional automakers becoming, for example, official assemblers and importers of the German BMW and Porsche. Or building cars together with the also British, formerly major aircraft manufacturer, Bristol Aeroplane Company and its hand-built luxury cars division. In virtue of its historical commercial links, Frazer-Nash expanded competences to armament and combat airplanes' massive parts productions, engineering consultancy and electric and hybrid vehicle technology. Several successor companies emerged, such as Nash & Thompson, Frazer-Nash Consultancy, Frazer-Nash Ltd or the group of Companies composed by Frazer-Nash Research Ltd and Frazer-Nash Energy Systems [209]–[211].

Frazer-Nash Research Ltd and Frazer-Nash Energy Systems have been working on the production of a range-extended electric powertrains mainly applied in Metrocab: a plug-in, range-extended electric cab for London, which was expected on the streets of the city since the beginning of 2016. Particularly, Frazer-Nash Energy System is supplier of the Electric Power Train components, among them batteries and the BMS, dc-dc converters, electric charger, electric machines, drives and the like [212], [213].

Frazer-Nash Research Ltd develops projects from concept through to low volume production and is part, since 1991, to the also British Kamkorp Group; which currently owns Bristol Cars Ltd, the London taxis manufacturer Metrocab and the lithium-ion cells manufacturer EAS, among others [210], [211].

4.4 Electro-mobility in non-automotive applications

Electro-mobility attains as a subject not only to passenger's light-duty vehicles. Activities can be found also for every other type transportation means, including maritime, aerospace applications, as well as many special vehicles. In this sense, some of the players providing lithium-ion energy storage solutions have identified this kind of niches and have successfully entered the market through it.

4.4.1 Electric bicycles, scooters and all-terrain vehicles: JTT Electronics LTD, Lithium BALANCE A/S and Ventec-iBMS.

An important BMS provider for electric bicycles, scooters and all-terrain vehicles is the Canadian JTT Electronics LTD. This company has spread in news and press releases about strategic partnership with GIO Motors – a Vancouver based company with Canada-wide distribution of their recreational equipment. For them, JTT Electronics LTD develops a maintenance-free 48 V, 25 Ah battery pack in conjunction with their P-Series BMS. As they claim, the P-series BMS, which can be applied for portable, low voltage lithium-ion battery packs as well as Uninterruptible Power Supply, is currently in mass production. Moreover, the X- and S- BMS series are typically used with low to high voltage battery packs for mobile applications, all-electric and hybrid electric vehicles, including city buses, and industrial machines [59], [214]–[216].

On this segment of the e-mobility market, Lithium BALANCE has done its part as well. Their first break through was with a 48 V Li-Ion battery managed by their own BMS, performing 157 km on a single charge of an electric scooter compared to only 40 km with the standard lead-acid battery pack. The 72 V-version of its BMS was released later in October 2007 [217]. Activities covered by the media in 2016 indicated a partnership together with OXIS Energy from UK. The aim: to build the first-ever prototype lithium-sulfur, e-scooter battery system, meant to be commercially available later at the Chinese market. The prototyped Lithium Sulfur battery has a capacity of 1.2 kWh [218].

Another interesting project is that one developed by Ventec-iBMS, in cooperation with its above mentioned partners in business Pragma Industries and Cycleeurope. The ultimate goal of the ALTER BIKE project: to market a hybrid, hydrogen fuel cells-electric bicycle in a number of 3.000 [201], [207], [219].

4.4.2 Agricultural Machines: Sensor-Technik Wiedemann GmbH – STW

Headquartered in Southern Germany, STW has been providing leading manufacturers of mobile, agricultural and other special machines with a wide product portfolio in automation, networking and electrification technology, for over 30 years. Just prior to the new millennium, the company also jumped into the electro-mobility. Its products portfolio comprises from the ESX family control units to the Power Board Distribution [220] Units and the powerMELA: a series of electric motors and drives with capacities from 40 to 140 kW, together developed with Baumüller [221]; additionally, sensors and telematics platforms.

With the combination of all these individual components, STW builds mobility solutions for electric and hybrid machinery and vehicles, including trains, harvesters, buses and snow groomers. Or for auxiliary mechanisms in larger mobile machines, such as fan and trailer drives. One of the relevant business partners in the field is Bernard Krone GmbH: a leading manufacturer of agricultural machinery founded in 1906, with headquarters in Lower Saxony, Germany, and subsidiaries in 4 countries including the USA. In this specific case, STW has acted as the development partner and supplier for central control units and motor bridge modules for forage harvesting agricultural machines. The company received the "Supplier of the Year Award" as best supplier in the Electronics category from Bernard Krone GmbH [222].

One of the latest products STW brought to the market is the mBMS for lithium-ion batteries: a modular off-the-shelf solution and a development basis for electrical and hybrid vehicles for road, floor conveyors or industrial mass storage devices for grid stabilization. In this field, STW cooperates with ElringKlinger AG, an important cars spare parts manufacturer with headquarters in Baden-Württemberg, Germany and 39 fully consolidated subsidiaries. STW cooperates with the e-mobility department at ElringKlinger AG on building battery modules with optional cooling and integrated electronic cell monitoring systems for 24 V, 48 V and up to 1,000 V in series [223], [224].

Other news talk about the participation of STW as a member of the Ethernet POWERLINK Standardization Group, porting the so-called POWERLINK real-time open-source protocol to the central control units of agricultural machines. The operation of the protocol is based on the CONNEX-TC3G module: a data management and telemetry module, also produced and developed by STW. This module supports communications via WLAN, Bluetooth and 2G/3G networks, which enables remote access to Cloud of Things platforms, such as the one maintained by Deutsche Telekom. The CONNEX-TC3G module facilitates the collection of information coming from control units and sensors of an agricultural vehicle, and takes care of the data transmission to the cloud. There, the gathered information can be logically linked and critical states of operation automatically recognized. STW developed similar activities with its so-called "machine.cloud" platform and the Nokia-Siemens network spin-off Cumulocity GmbH: a software solution developer in the Machine to Machine and Internet of the Things communication sector [225]–[229].

4.4.3 Heavy weight transport and lifting: Lithium BALANCE A/S and Navitas Systems

Lithium BALANCE A/S partnered in 2011 with Toyota Material Handling Europe: a relevant-global OEM, also in material handling solutions, for the development of the lithium-ion powered BT Reach Truck and its use in a -25°C stores. Lithium BALANCE designed, manufactured and supplied a complete battery pack with a standard battery to truck interface and its s-BMS. The solution was tested at the Danish cold store and distributor SuperGros – a EUR 2.3 billion per year in revenues-company, with around 1150 employees. SuperGros reported then 50% of savings on initial battery investments, the extension of the service shift from 5 hours to 9 hours without recharging and the possibility of 24 working hours for the machine, with the introduction of the so-called Opportunity Charge Routine. All this was not possible with the old working system, based on the periodic replacement of lead-acid batteries [230].

Similarly, Navitas Systems launched in 2015, at the Battery Show in Novi, Michigan, the Starlifter: a low voltage, large-format and high-energy lithium battery with its corresponding BMS. These series of deep cycle lithium-ion energy storage systems can handle a voltage range from 36 V up to 80 V, while offering capacity values in the orders of magnitude like those found in HEVs – from 10 kWh to 30 kWh. The Starlifter battery packs provide an active balancing scheme and are meant to replace heavy-duty, traction, lead-acid batteries in Class I and Class II forklifts. According to press releases from 2015, the Starlifter was tested by three of the five top global forklift manufacturers. In one of these cases, for example, Navitas Systems was awarded a subcontract from Raymond Corporation in 2014 for a cold storage environment demonstration of the Starlifter [231]–[233].

According also to press releases from late 2016, the company was awarded with the deployment of the Starlifter lithium-ion battery packs in forklifts at the facilities of the Eastern Distribution Center – in a major location – of the Defense Logistics Agency of the US army. The location consists of a 1.7 million square feet and a high-ceiling building, with 122 dock doors and over 322,000 storage locations. Material is moved there throughout the main building via 4.5 miles of conveyor lines, 5.3 miles of tow line pulling 1,100 carts for the automated cart system, and over 400 pieces of conventional, manually-operated forklifts, order pickers, and carts. The Eastern Distribution Center typically operates six days a week with two shifts per day. This particular project enabled the largest worldwide performance assessment for the Starlifter vs. lead acid forklift batteries, in a highly-demanding, material-handling scenario [234].

Among their most renowned partners, Navitas Systems considers Samsung, A123 Systems, Continental Energy Solutions and the United States Defense Department [235], [236]. The product portfolio of Navitas Systems includes, among others, the PowerForce lithium auxiliary battery system; designed to eliminate excessive idling consumption in vehicles such as ambulances and other emergency vehicles. It provides key-off battery support for onboard electronic systems, thus saving significant amounts of fuel without diminishing performance. In 2015, for example, the City of Detroit engaged Navitas Systems for the implementation of the PowerForce on its Ambulances fleet [233], [237].

A major business area for Navitas Systems also consists of the production of ruggedized lithium battery products for military and industrial markets. Its military vehicle batteries Ultanium are used in tanks, Humvees and tactical vehicles. And are meant to be the replacement of these vehicles' traditional lead-acid batteries, providing additional capabilities well beyond the lighting and ignition functions of the older ones [233], [236], [238].

4.4.4 Maritime e-mobility: REAP – Renewable Energy Advanced Propulsion – Systems and Lian Innovative

REAP Systems' technological developments have, in many cases, headed to the water. Starting with underwater vehicles it is possible to track media information back to the possibility of a solid and long term cooperation between REAP Systems and Saab Underwater Systems; a business unit within the Swedish Saab group with close and long term cooperation with the Royal Swedish Navy. REAP Systems was, according to press releases, the first choice for designing and delivering key components for a SEAL Carrier [239]–[243].

But one of the most ambitious and recent technological developments from REAP Systems aims to bring a less pollutant water taxi to Venice, Italy, by making them hybrid electric. The UNESCO World Heritage city has approximately 20.000 leisure craft and 550 taxi boats, serving around 32 million visitors every year. All are currently diesel-powered, meaning this that Venice suffers from high levels of air, water and noise pollution; which affects the architecture and health of both, residents and tourists alike. The system, designed with the support of Southampton University and RIB maker Scorpion, uses a Hyundai diesel engine paired with an electric motor, a lithium-ion battery pack and a control unit [244]–[246].

Since its foundation by Dr. Dennis Doerfell as spin-off from the Southampton University [247], REAP Systems has been producing and commercializing a 650V central Battery Management System for up to 168 cells using their off-the-shelf BMS. It plugs into 8 cell battery modules available from Kokam and can be used in larger vehicles, boats, submarines as well as automobiles [248].

A second example of an organization, which works with maritime e-mobility applications, is the Chinese, Shenzhen-based Lian Innovative. This company was founded as an innovation and engineering company with core competences on the subject of underwater robots [249].

4.4.5 Solar races and other electric challenges: REAP Systems, Ventec-iBMS and Tritium Pty Ltd

Competitions have traditionally been test polygons for the latest achievements in many branches of science and technology. And electro-mobility is not the exception. Many are the examples of competitions, where different kind of electric vehicles are expected to prove the superiority of newest developments. Among those contest, the FIA Formula E Championship is probably one of the most demanding and famous [250]. Another contest of this type is the Formula Zero Championship, the world's first hydrogen fuel cell race series where, for example, REAP Systems supported the Imperial Racing Green team from the Imperial College London [251], [252]. Or the attempt of Venturi Automobile in 2013 of breaking the speed world record for an electric vehicle – 600 km/h with its Jamais Contente [253], [254]. But there are more.

Solar cars contests were born in Australia already two decades ago, with the aim of testing the ultimate boundaries of energy efficiency. And nowadays, when the spirit of such a great initiative has spread all over the world with notable international challenges taking place in USA, Japan and South Africa, the innovations there shown lie at the heart of commercial electric cars.

Of course, off-the-shelf BMS manufacturers have joined forces with solar vehicle teams, in contests such as the Moroccan and the Abu Dhabi Solar Challenge. One of the examples is the one from Ventec-iBMS and the French Eco Solar Breizh team to these two competitions [255], [256]. To the Australian World Solar Challenge competition, REAP Systems partnered first with the Solar Fox team from the University College London, in 2007, while from 2009 to 2015 with the Nuon Solar Team from the Technical University of Delft [257]–[260]. The aim: building a car capable of crossing Australia with no more than six square meters of solar panels, albeit starting with a fully charged-5kWh battery pack.

Another BMS manufacturer, actively supporting teams from many corners of the world to the Australian World Solar Challenge, is Tritium Pty Ltd. The company was founded in 2001 by former competitors – the SunShark team – from the University of Queensland. Since having experienced in 1999 the grueling 3000 km race from Darwin to Adelaide in a self-designed and built solar vehicle, the idea behind the foundation of the company was commercializing and improving the electronic technology they developed for their own. To the date, the company is providing their technological solutions for more than half of the international participants in the biennial Australian contest. Some examples are the teams "Arrow" from the University of Queensland, "Blue Sky Solar Racing" from the Toronto University and the one from the University of Applied Sciences in Bochum, Germany [261]–[263].

The product portfolio Tritium Pty Ltd offers to the competitors comprises from the three phase's motor controllers WaveSculptors, to electronic control units, CAN Bus-Ethernet bridges, its IQ BMS for lithium-ion and lead acid battery packs, LCD displays and a stock of miscellaneous products, for aiding in connecting the system together.

4.4.6 Charging stations: Tritium's VEEFIL charger

But neither the participation of Tritium Pty Ltd in the World Solar Challenge nor any of the above mentioned products have brought more media attention and value to this company than its VEEFIL, 2nd class, 50kW DC electric charger. As the culmination of 10 years of technological development, the company brought a product to the market with the capability of adding 50 km range to an Electric Vehicle in 10 minutes, while being able to properly work at extreme temperatures -20°C to 50°C – due to its liquid cooling system. The Tritium stations are able to charge all cars equipped for DC charging, using the included SAE-Combo or the CHAdeMO connectors [264]–[266].

The VEEFIL super charger received immediate acceptation in many corners of the world, enabling Tritium Pty Ltd to develop important partnerships for its wide commercialization. For the Chinese market, the Australian company has come together with the Shanghai-based and electric products manufacturers "Surpass Sun Electric Co. Ltd (SSE)", a leading company in China since 1997 [267]–[269]. The distribution of the "VEEFIL" has debuted for its commercialization also in Europe, in this case together with the German E-WALD [268], [270]–[272]; a fast-growing e-car sharing organizations which currently owns a fleet of nearly 200 EVs, in addition to a network of over 140 charging stations across Germany, Austria and Switzerland. In North America, the Australian company partnered with ChargePoint: the world's largest and most open Electric Vehicle charging network. The "VEEFIL" charging stations are currently being installed on major routes across the USA and Canada, and will be part of the charging network with more than 31,000 stations [273]–[279].

4.4.7 Electric car conversions or prototyping as experimental proofs of concept: Clean Power Auto LLC, Lithium BALANCE A/S, Sensor-Technik Wiedemann – STW and other examples

Some of the third party BMS manufacturers and suppliers started their technological development with the conversion of conventional ICEV into electric cars.

One representative example is that one of Clean Power Auto LLC. The company was founded in 2009 in the USA, when large prismatic Lithium Iron Phosphate (LiFePO4) cells became widely available. Clean Power Auto LLC developed the so-called MiniBMS, initially to be used in their own EV conversions. Over time, the entirety of their business was completely turned into BMS production, expanding to other applications such as marine, solar banks, and the like.

Clean Power Auto LLC partnered later on with Lithionics Battery – a battery manufacturer – to continue activities in the field of BMS development for a variety of markets and applications. Currently, because of their partnership with Lithionics, the company does not longer offer direct BMS sales in large volumes, to system integrators and resellers; only to hobbyist and at their own risk. The company recommends all customers interested in complete battery solutions to purchase from Lithionics Battery instead [280].

Lithium BALANCE A/S has also converted series vehicles. Examples are an electric prototype from Lotus Engineering, a subsidiary of Proton Cars, the Malayan cars manufacturer. The company performed these activities in 2009, which allowed the release for production and sales of a demonstrated, scalable BMS platform for electric cars and other high voltage applications [217], [281].

Lithium BALANCE A/S has also provided All Green Vehicles (AGV) with its Battery Management Systems for two type of products [282]:

- The AGV Connect Light Goods Vehicle – based on the Ford Transit Connect – with 130 km/h top speed, 130 km range and a 25.7 kWh battery pack with lithium-ion polymer pouch cells. The vehicle was meant to work in urban deliveries with the Dutch power utility ENECO.
- The AGV MAN Heavy Goods Vehicle, with a modular 120kWh battery pack.

AGV is the leading supplier of high speed electric vehicles in the Netherland and the Benelux region – Belgium, the Netherlands, and Luxembourg – which converts and sells electric vehicles from a variety of OEMs including Ford, MAN and Oullim Motors, in Korea. AGV has also been involved in the conversion of Toyota Priuses to plug-in hybrids and the development of an electric version of the Korean sport car Oullim Spirra. With headquarters in the Netherlands, AGV has a current production capacity of over 600 vehicles/year.

Another conversion example was the agricultural showcase, glass tractor. In this case, Sensor-Technik Wiedemann – STW provided the demonstrator with a complete solution for the power electrification of the machine, including not only the BMS, but also the control units, sensors, telematics platforms, power distribution units and batteries, among others. The tractor was equipped with STW's powerMELA concept which, in conjunction with the diesel engine, conformed a hybrid system tuned to operate at the optimum efficiency point of operation. The glass tractor was also equipped with data management modules for the transmission of relevant information to online cloud servers [283], [284].

Other companies participating in the past in car conversions are the following:

- Tritium Pty Ltd: the Australian company participated from the conversion of a General Motors' Holden Commodore with minimal impact to the vehicle chassis, by EV Engineering: a consortium of automotive industry companies with base in Melbourne. In the first phase of the project, seven electric Holden Commodores with the IQ Battery Management System from Tritium Pty Ltd were delivered and demonstrated in Australia. In a more ambitious second phase of this project, a small-scale production of 120 vehicles with similar characteristics was expected [285].

- REAP systems' Dennis Doerfell converted an Internal Combustion Engine vehicle Ford Fiesta into a hybrid one in 2003, and a 1998-VW into a Battery Electric Vehicle in 2005 [286], [287].
- Delphi Automotive PLC and Continental AG have showcased their 48 V mild hybrid solutions by the conversion of series ICEV: Delphi Automotive PLC in a Honda Civic [186], [288], while Continental AG in a VW Golf [289], [290].
- Elithion Inc.: the company was founded by Davide Andrea – author of the book "Battery Management Systems for Large Lithion-Ion Battery Packs. As they claim, Elithion is prepared to ramp up production to match the ramp up of the EV manufacturers. Elithion Inc. has supplied Russian AvtoVaz with 100 Lithiumate BMSs for its Lada EV. Also, the production of the electric Fiat 500 incorporates Li-ion batteries, which are managed by the Lithiumate BMS [291].
- Manzanita Micro Power Systems: A small company with headquarters in Washington, USA, which started making conversions of conventional ICEVs into BEVs and developed later as a BMS manufacturer. As for Tritium Pty Ltd., its most important products seem to be chargers also. Among the conversions into electrics Manzanita Micro Power Systems participated in are a two-doors Sedan-Ford Pinto and a Ford Fiesta, both from 1978 [292].

4.4.8 Wireless communication networks in BMS

In a significant number of commercially available modular BMS, wired solutions for communication among the architectural layers are found. Unfortunately, this implementation can be complicated and expensive due to the large number of connections and wires, which are not easily routed from the measurement points to the Master module. Keeping track of the wires and their correct location, when performing maintenance or reparation activities, can be complicated as well [293].

In opposition, a wireless communication system might increase the system reliability by the reduction of wires while improving safety, since no physical connections among layers are necessary. Implementing a wireless communication network in Battery Management Systems provides the following advantages over the wired solution [294].

a) It makes possible to operate the slave modules of the BMS in conjunction with their corresponding cells as standalone units.
b) Due to a), monitoring activities from earlier stages of the production of the cells and packs, as well as data acquisition and local storing capability during the manufacturing process, are possible.
c) A wireless strategy provides insightful information in terms of manufacturing tolerances and allows early sorting activities for cells with similar characteristics, what improves the quality of the resultant battery modules.
d) It allows real time transmission of secure encrypted data to an unlimited number of modules and the unlimited expansion of the battery total capacity, without introducing changes to the wiring harness.

Due to these advantages, organizations such as the Lawrence Livermore National Laboratory [294], LION Smart GmbH [295], [296], Elite Power Solutions [293] and Navitas Solutions [63] have produced, showcased and, eventually, patented wireless Battery Management Systems. In the case of Navitas Solutions, the company has even patented a propriety communication protocol – the Wireless Battery Area Network or WiBaANTM – which allows simplified battery pack design while enabling highly reliable and secure data communication with the master controller [297].

4.4.9 Third party BMS manufacturers and standards compliance

To commercialize BMS for electric vehicles, compliance with automotive standards needs to be guaranteed; essentially with those standards which are safety related. For well-known automaker parts suppliers, providing their products in full compliance with the standards of the industry should be not a surprise. On the other hand, the same does not necessarily happen with minor-third party BMS manufacturers. Albeit some seem to be working also in this direction. The most relevant examples are gathered below.

- Lithium BALANCE A/S has received the ISO 9001 certification from Bureau Veritas in 2015 [298], meaning this an in-place and effective quality management system; additionally, the Green Smiley from the Danish Working Environment Authority [299], which certifies that facilities and procedures comply with Danish Safety Legislation. These facts together with [300] substantiate that Lithium BALANCE A/S could be making solid steps in the direction of certifying their products per the ISO 26262, the safety standards for electric and electronic equipment in the automotive industry.
- Also from press releases, it seems to be the case that Sensor-Technik Wiedemann – STW, produce their electronic devices in compliance with IEC 61508. The company claims that, "as a supplier of solutions for mobile machines, utility vehicles and special machines, STW (…) shoulders the increased development expense for certification in accordance with the Basic Safety Standard IEC 61508. In this way STW can provide customers with the option of securing their investments and applying our products in their long-term applications" [301].
- Navitas Solutions has engineered its wireless BMS for compliance with the ISO26262. The product, as they claim, is also compliant with CISPR25 for radiated emission tests, with ISO11452 for radiated immunity tests, and with ISO10605/16750 for electrical reliability and environmental tests [63].
- I + ME ACTIA also incorporates in all its developments, the safety requirements of the ISO 26262 certification and of the standards R100, guaranteeing both compliant electronics for electric vehicle [302].
- BMS chip vendors such as:
  1. Intersil: produces a dedicated IC for 12-cell battery pack manager – the ISL78600 - with automotive grade AEC-Q100 [303] , which can be used as a standalone part in ASIL compliant systems. Or deployed in conjunction with the complimentary ISL78610 for higher ASIL ratings, or in systems requiring an independent backup solution.
  2. Similarly, Linear Technology produces the LTC6802 family of Multicell Battery Stack Monitors, also designed for Automotive and Transportation Applications – AEC-Q100 [304].
  3. NXP Semiconductors: produces the MC33771 – a 14 channels, Li-Ion battery cell stack monitoring integrated circuit, designed for automotive and industrial applications [305].

5 Conclusions and Recommendations

The study in the section 1 gave on overview of the BMS currently available on the market, mainly focusing on the EV application domain. A set of 32 available systems was categorized and analyzed according to their topology and other key features. Due to the quality of publicly available information, the study emphasized BMS of smaller manufacturers and engineering companies for prototypes, small batch and pilot series production, which often reveal more detailed information about the technical specifications and structure of their BMS.

The analysis of the market showed a large variety of BMS for automotive applications. It thus seems likely that standardization of such BMS components could lead to significant scale effects and therefore further cost improvements [7].

From the analysis of the commercial products, the following features for a future, standardized automotive BMS seem likely:

- Modular hardware architecture, capable of handling up to 1000V on pack level
- Measurement boards/ICs (CMUs) with ability to handle cell chemistries up to 5V
- CAN communication, possibly wireless communication (if safety, security, EMV and timing requirements can be met)

As noted, the comparison of BMS remained incomplete as it turned out to be not possible to gather detailed enough technical information for many OEMs and their suppliers for BEV and HEV applications, including some of the largest EV car makers like Volkswagen, Toyota, Renault-Nissan, and Tesla.

However, the success of a standardized BMS proposal will crucially depend on its adoption by these large and influential market players. Therefore, although it will be challenging, it is of paramount importance to make efforts to approach these OEMs and suppliers, in order to gain more information about their BMS activities, and join efforts in standardization activities.

During the development of a BMS for an EV, there are various aspects to be considered to assure the safe operation of the battery system. This includes especially measures to reduce the risk of component faults or design flaws to an acceptable level – functional safety – as well as measures to prevent unauthorized manipulation – security. Section 2 introduced key concepts of the ISO 26262 Road vehicles – Functional Safety standard and its application to automotive BMS development. This ISO 26262 standard, which comprises about 480 pages, is formulated in a very comprehensive and general manner such that it can be used both for the development of a complete vehicle as well as for individual automotive components.

In the market overview in section 4, it was noticed that only few companies currently offer a BMS with a specified automotive safety integrity level. It can be concluded that it is difficult to apply the existing ISO standard directly to BMS. One reason is that BMS are offered for quite different purposes, for example both stationary and mobile embedded applications, e.g. automotive, aerospace, etc. However, the ISO 26262 demands that the safety requirements are to be considered and met with respect to the specific application context. If this application context is not explicitly specified, the development must be carried out according to the safety element out of context (SEooC) concept, which requires a comprehensive and careful definition of all interfaces and their possible uses in the required documentation. The certification of the BMS, especially the interface definitions and assumptions, must then often be reconsidered and checked again in the development process of the overall application, e.g. stationary or mobile battery pack.

To date, there exist no specific functional safety standards or guidelines for the development of BMS. Although there exist some general guidelines for the certification of the functional safety of a generic battery management system [306], these only exemplary illustrate individual methods of the norms IEC 61508 and ISO 26262. In the view of the findings of this study, these approaches can only be supportive measures in the development process, and are not sufficient by themselves to reach an ASIL certification of a BMS according to ISO 26262. Currently, the development of a revised ISO 26262: 2011 norm is under way. It is likely that this revision will contain more detailed recommendations for carrying out a safety analysis especially for the increasingly important software parts of electrical and electronic devices. Through analysis process, it became clear that there lacks a functional safety standard that specifically fits the development of BMS. Frequently, the development concept safety element out of context was used in publications, which is only a special and restricted case of development within ISO 26262.

It would therefore be helpful in the future to develop a specific standard for BMS, based on the standards for functional safety (IEC 61508, ISO 26262, DO-254 / DO-178C20) for electrical and electronic applications. This standard could be prepared in a joint effort of OEMs, BMS manufacturers, and testing organizations.

In addition to functional safety – which considers system-internal threats due to design flaws and malfunctioning components – as BMS are increasingly becoming networked and distributed systems, also external threats to the system become more and more important. In fact, embedded control systems in modern vehicles are increasingly targeted by cyberattacks, and in the case of BMS, a manipulation of the measurement data that it receives or a corruption of its control actions could turn out catastrophic.

It is therefore increasingly important that IT security concerns will also be taken into account in BMS development. Some basic principles include the use of encryption, certification, separation of communication channels and use of gateways to complicate access to information, plausibility checks for critical BMS control commands, as well as access authorization mechanisms that prevent e.g. unauthorized flashing of new BMS firmware.

From the analysis carried out in section 3, it has been ascertained that, on electric vehicles technologies and their corresponding segments and trends, the group of the most important intellectual property holders is composed by traditional automakers, consumer electronics and cells manufacturers. The most relevant electric vehicles markets are usually indicated as well by the preferred jurisdiction to these OEMs for patent filling activities, being the most active the Chinese scenario, followed then by Japan, US and Europe in this order.

Within the segment of EV technologies, batteries, power supply systems, propulsion, and control units are the most relevant trends for patents fillings. Activities on EV batteries technologies comprise an important amount of registrations in the topics of battery monitoring, battery controlling and battery temperature regulation. Within this group, top patent holders seem to be the worldwide known Toyota, Honda, Nissan, General Motors, Hyundai, and Bosch, as well as battery manufacturers like Panasonic, LG, Sanyo, and Samsung.

In the topics of batteries and cells monitoring the determination of the lithium-ion cells states, namely SOC and SOH, has been as well a subject of intellectual property registration. In this sense, the above-mentioned OEMs have managed to protect a plurality of methodologies with base in an extensive set of fundamental tools, from many of the fields in science and technology. The methodologies range from the simplest Ampere-hour counting and open circuit voltage recalibration techniques to the more elaborated strategies with base in artificial intelligence methods, nonlinear observers, and filters. These are associated to equivalent circuit models of different orders of complexities or intensive experimental activities.

Each registration attempts to solve the important problem of cells monitoring by conveniently exploiting the vehicle's operational scenario – driving, charging or parking – while avoiding or improving known issues in relation to the employed tool.

In this sense, the employment of closed loop estimation systems, such as those built on the dual Kalman filter or nonlinear observers, seem to be most recommended. The utilization of artificial neural networks is preferred as well for applications in hybrid electric vehicles, where accurate states estimations are mandatory. In any of the cases, an initial calibration of the selected model from experimental data seems to be necessary, either for the parameterization of an equivalent circuit model, a fuzzy inference system, or a Wavelet neural network. It is also recommended endowing any of the preferred strategies with adaptation capabilities, in order to maintain the adequate accuracy of the monitoring as the cells are ageing, e.g. training artificial neural networks in a battery electric vehicle's onboard setup.

From a vast ecosystem of more than 150 active, relevant players all over the world in the BMS market [139]–[145], [307]–[309], only the BMS and the related intellectual property produced by the 29 manufacturers in Table 5.1, and the cell stack monitors from the 11 BMS chip suppliers in Table 5.2, have been considered in this study. Their main descriptors have been collected and shown in these tables. A complete relation with all the identified players can be found in the tables in Annex B.

The description of the BMS market within section 4 was carried out based on important media sources such as specialized journals and technological magazines, as well as their corresponding on-line portals. In addition to this, information published by the relevant players through their own distribution channels in news, blogs or press releases has been an important source of information. Based on this collected information:

- The BMS supply toolchain to important EVs manufacturers was exemplified with some of its known relevant players.
- The relevant, third party – automotive – BMS manufacturers were identified as well as their products. Their relevant R+D activities have been illustrated, with information provided by news and press releases.
- Also from the news, trendy and relevant activities to the automotive BMS market were covered in the section, such as those of wireless communications or automotive standards compliance.

#	BMS manufacturer	Headquarters	Founded	Parent organization
1	LG Chem Ltd. [310]	Seoul, South Korea	1947	LG Corp
2	Samsung Sdi Co. Ltd. [311]	South Korea	1970	Samsung Group
3	General Motors Global Technology Operations Inc. [312]	Detroit, Michigan, USA	2009	General Motors Company
4	Ford Global Technologies LLC. [313]	Dearborn, Michigan, USA	2002	Ford Motor Company
5	Tesla Motors Inc. [314]	Palo Alto, California, USA	2003	
6	Nissan Motor Company Ltd. [315]	Yokohama, Kanagawa Prefecture, Japan	1933	Renault S.A.S.
7	Renault S.A.S. [316]	Boulogne-Billancourt, France.	1898	
8	Mitsubishi Motors Corporation [317]	Minato, Tokyo, Japan	1917	Mitsubishi Group
9	Toyota Motor Corporation [318]			
10	Denso Corporation [319]	Kariya, Aichi, Japan	1949	Toyota Motor Corporation
11	Delphi Automotive PLC, [320]	Gillingham, Kent, UK	1994	
12	Preh GmbH, [321]	Bad Neustadt an der Saale, Bavaria, Germany	1919	Joyson Electronic Corp.
13	Ventec-iBMS, [202]	Mérignac, FRANCE	2009	
14	JTT Electronics Ltd., [214]	Vancouver, Canada	2010	
15	Lithium BALANCE A/S, [217]	Smørum, Denmark	2006	
16	Sensor Technik Wiedemann, STW GmbH, [322]	Kaufbeuren, Bavaria, Germany	1985	

17	REAP Systems, [323]	Southampton, UK	2003	
18	Lian Innovative, [324]	Shenzhen, China	2000	
19	Tritium Pty Ltd., [325]	Queensland, Australia	2001	
20	Elithion Inc., [326]	Colorado, USA	2008	
21	LION Smart GmbH, [327]	Garching, Bavaria, Germany	2008	LION E-Mobility AG
22	Elite Power Solutions, [328]	Arizona, USA	2008	
23	Navitas Solutions, [329]	New Jersey, USA	2010	
24	I+ME ACTIA GmbH, [330]	Braunschweig, Germany	1986	ACTIA Group
25	Ewert Energy Systems, Inc. – The Orion BMS, [331]	Illinois, USA.	2011	
26	Valence Technology, [332]	Austin, Texas, USA	1989	
27	Manzanita Micro Power Systems, [292]	Kingston, Washington, USA	Before 2007	
28	EVPST Co. Ltd., [333]	Guangzhou,China	1999	
29	AshWoods Energy, [334]	Exeter, UK	2009	Vayon Group

Table 5.1. Relevant information of the BMS manufacturers, whose products habe been considered in the study.

#	BMS chips supplier	Headquarters	Founded	Parent organization
1	Linear Technology, [304]	California, USA	1981	
2	Freescale Semiconductor Inc., [335]	NXP Semiconductors	2004	NXP Semiconductors
3	NXP Semiconductors, [305]	Eindhoven, Netherlands	2006	Qualcomm
4	O2 Micro International Ltd., [336]	Grand Cayman, Cayman Islands	1995	
5	Intersil Corporation, [303]	California, USA	1999	
6	Maxim Integrated, [337]	California, USA	1983	
7	Texas Instruments, [338]	Texas, USA	1951	
8	AMS-Austriamicrosystems-AG, [339]	Unterpremstätten, Austria	1981	
9	Renesas Electronics, [340]	Tokio, Japan	2002	
10	Atmel Corporation, [341]	California, USA	1984	Microchip Technology
11	Analog Devices, [342]	Massachusetts, USA	1965	

Table 5.2. Relevant information of the BMS chips suppliers, whose products have been considered in the study.

6 REFERENCES

[1] D. Andrea, *Battery management systems for large lithium-ion battery packs*. Boston: Artech House, 2010.

[2] B. Scrosati, J. Garche, and W. Tillmetz, Eds., *Advances in battery technologies for electric vehicles*. Amsterdam: WP, Woodhead Publishing/Elsevier, 2015.

[3] G. L. Plett, *Battery management systems. Vol. 2. Equivalent-Circuit Methods.*, vol. 2. 2016.

[4] M. Jung and S. Schwunk, "High End Battery Management Systems for Renewable Energy and EV Applications," *Green*, vol. 3, no. 1, Jan. 2013.

[5] M. Brandl *et al.*, "Batteries and battery management systems for electric vehicles," 2012, pp. 971–976.

[6] P. Weicker, "Chapter 5 Architectures," in *A systems approach to lithium-ion battery management*, Boston: Artech House, 2014, p. 60,62.

[7] Robert Ratz, "BMS System Benchmark and Standardization." Ricardo Inc., Mar-2015.

[8] P. Weicker, "Chapter 5.2 Distributed," in *A systems approach to lithium-ion battery management*, Boston: Artech House, 2014, p. 61.

[9] D. Andrea, "Chapter 2.3.4 Distributed," in *Battery management systems for large lithium-ion battery packs*, Boston: Artech House, 2010, p. 48.

[10] Jim Douglass, "Battery Management Architectures for Hybrid/Electric vehicles," *Electronic Product Design*, Mar-2009.

[11] Greg Zimmer, "Wireless battery management systems highlight drive for higher reliability \textbar EDN," *EDN Network*, 25-Nov-2016. [Online]. Available: http://www.edn.com/design/power-management/4443071/Wireless-battery-management-systems-highlight-industry-s-drive-for-higher-reliability. [Accessed: 14-Feb-2017].

[12] R. Korthauer, Ed., *Handbuch Lithium-Ionen-Batterien*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013.

[13] H. Sattler, "Elektrische Sicherheit," in *Handbuch Lithium-Ionen-Batterien*, R. Korthauer, Ed. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013, pp. 299–306.

[14] A. Jossen, V. Späth, H. Döring, and J. Garche, "Reliable battery operation — a challenge for the battery management system," *J. Power Sources*, vol. 84, no. 2, pp. 283–286, Dec. 1999.

[15] P. Weicker, *A systems approach to lithium-ion battery management*. Boston: Artech House, 2014.

[16] European Commission Participant Portal, "Electric vehicles' enhanced performance and integration into the transport system and the grid. GV-8-2015," 12-Nov-2013. [Online]. Available: http://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/gv-8-2015.html. [Accessed: 09-Jan-2015].

[17] "Global Electric Vehicle Outlook 2016," International Energy Agency, OECD/IEA 2016, 2016.

[18] James Ayre, "$145 kWh Battery Cell Costs At Chevy Bolt Launch, GM Says," *EV Obsession*, 10-Apr-2015. [Online]. Available: http://evobsession.com/gm-145-kwh-battery-costs-bolt-ev-launch/. [Accessed: 28-Nov-2016].

[19] Jeff Cobb, "Tesla Projects Battery Costs Could Drop To $100/KWH By 2020," *hybridCARS*, 18-Jun-2015. [Online]. Available: http://www.hybridcars.com/tesla-projects-battery-costs-could-drop-to-100kwh-by-2020/. [Accessed: 28-Nov-2016].

[20] United States Department of Energy, "About EV Everywhere," 2016. [Online]. Available: http://energy.gov/eere/eveverywhere/about-ev-everywhere. [Accessed: 28-Nov-2016].

[21] Brian Fuller, "GM calls back Chevy Volts to fix battery problems," *EETimes-Breaking News*, 05-Jan-2012. [Online]. Available: http://www.eetimes.com/document.asp?doc_id=1260896. [Accessed: 28-Nov-2016].

[22] Mike M. Ahlers, Aaron Cooper, and Thom Patterson, "Another battery incident troubles Boeing's 787 Dreamliner," *CNN Travel*, 14-Jan-2014. [Online]. Available: http://edition.cnn.com/2014/01/14/travel/787-dreamliner/. [Accessed: 28-Nov-2016].

[23] DANIELLE IVORY, "Federal Safety Agency Ends Its Investigation of Tesla Fires," *The New York Times - BusinessDay*, 28-Mar-2014. [Online]. Available:

http://www.nytimes.com/2014/03/29/business/safety-agency-ends-investigation-of-tesla-fires.html?_r=1. [Accessed: 28-Nov-2016].
[24] Fred Lambert, "Tesla will update the Model S software for safer charging following a Supercharger fire," *electrek*, 17-Mar-2016. [Online]. Available: https://electrek.co/2016/03/17/tesla-supercharger-fire-update-software-short-circuit/. [Accessed: 28-Nov-2016].
[25] Fred Lambert, "Tesla Model S catches on fire during a test drive in France," *electrek*, 15-Aug-2016. [Online]. Available: https://electrek.co/2016/08/15/tesla-model-s-catches-fire-test-drive-france/. [Accessed: 28-Nov-2016].
[26] Tyler Durden, "Tesla Spontaneously Catches Fire, Burns Down During Test Drive In France," *ZeroHedge*, 15-Aug-2016. [Online]. Available: http://www.zerohedge.com/news/2016-08-15/tesla-spotaneously-catches-fire-during-test-drive-france. [Accessed: 28-Nov-2016].
[27] EVERLASTING Consortium, "Electric Vehicle Enhanced Range, Lifetime and Safety Through Ingenious battery management- EVERLASTING," Description of Work 713771, Jan. 2016.
[28] A. Farmann, W. Waag, A. Marongiu, and D. U. Sauer, "Critical review of on-board capacity estimation techniques for lithium-ion batteries in electric and hybrid electric vehicles," *J. Power Sources*, vol. 281, pp. 114–130, May 2015.
[29] Y. Barsukov, "Battery Cell Balancing: What to Balance and How," presented at the Portable Power Design Seminar, 2006.
[30] A. Manenti, A. Abba, A. Geraci, and S. Savaresi, "A New Cell Balancing Architecture for Li-ion Battery Packs Based on Cell Redundancy," *IFAC Proc. Vol.*, vol. 44, no. 1, pp. 12150–12155, Jan. 2011.
[31] W. Waag, C. Fleischer, and D. U. Sauer, "Critical review of the methods for monitoring of lithium-ion batteries in electric and hybrid vehicles," *J. Power Sources*, vol. 258, pp. 321–339, Jul. 2014.
[32] M. Berecibar, I. Gandiaga, I. Villarreal, N. Omar, J. Van Mierlo, and P. Van den Bossche, "Critical review of state of health estimation methods of Li-ion batteries for real applications," *Renew. Sustain. Energy Rev.*, vol. 56, pp. 572–587, Apr. 2016.
[33] M. Uno and K. Tanaka, "Influence of High-Frequency Charge–Discharge Cycling Induced by Cell Voltage Equalizers on the Life Performance of Lithium-Ion Cells," *IEEE Trans. Veh. Technol.*, vol. 60, no. 4, pp. 1505–1515, May 2011.
[34] F. M. Kindermann, A. Noel, S. V. Erhard, and A. Jossen, "Long-term equalization effects in Li-ion batteries due to local state of charge inhomogeneities and their impact on impedance measurements," *Electrochimica Acta*, vol. 185, pp. 107–116, Dec. 2015.
[35] J. Wen, Y. Yu, and C. Chen, "A Review on Lithium-Ion Batteries Safety Issues: Existing Problems and Possible Solutions," *Mater. Express*, vol. 2, no. 3, pp. 197–212, Sep. 2012.
[36] H. P. G. J. Beelen, L. H. J. Raijmakers, M. C. F. Donkers, P. H. L. Notten, and H. J. Bergveld, "An Improved Impedance-Based Temperature Estimation Method for Li-ion Batteries∗∗This work has received financial support from the H2020 programme of the European Commission under the grant 3CCar and from Dutch Ministry of Economic A_airs under the grant ADEM (A green Deal in Energy Materials).," *IFAC-Pap.*, vol. 48, no. 15, pp. 383–388, 2015.
[37] M. Hammer *et al.*, "Development of Safe Energy Storage System for Small Electric Vehicles," presented at the Conference on Future Automotive Technology COFAT 2014, Munich, 2014.
[38] G. Hofmann and G. Scharfenberg, "Random Hardware failure compliance of a cell balancing circuit with the requirements of automotive functional safety," presented at the Applied Electronics (AE), 2015 International Conference on, Pilsen, Czech Republic, 2015.
[39] R. Langner, "Stuxnet: Dissecting a Cyberwarfare Weapon," *IEEE Secur. Priv. Mag.*, vol. 9, no. 3, pp. 49–51, May 2011.
[40] David Z. Morris, "Tesla-Stealing Hack is about Much More than Tesla," *Fortune News*, 26-Nov-2016. .
[41] A. Wright, "Hacking cars," *Commun. ACM*, vol. 54, no. 11, p. 18, Nov. 2011.
[42] Chris Clarke, *Software Security and the Connected Car*. .
[43] Q. Wang, P. Ping, X. Zhao, G. Chu, J. Sun, and C. Chen, "Thermal runaway caused fire and explosion of lithium ion battery," *J. Power Sources*, vol. 208, pp. 210–224, Jun. 2012.

[44] D. H. Doughty and E. P. Roth, "A General Discussion of Li Ion Battery Safety," *Interface Mag.*, vol. 21, no. 2, pp. 37–44, Jan. 2012.
[45] F. Larsson and B.-E. Mellander, "Abuse by External Heating, Overcharge and Short Circuiting of Commercial Lithium-Ion Battery Cells," *J. Electrochem. Soc.*, vol. 161, no. 10, pp. A1611–A1617, Jul. 2014.
[46] H. J. Stadlbauer, "Übertragbarkeit einer empirischen Sicherheitslandkarte beim Wechsel eines Zellsystems," Semesterarbeit, Technische Universität München, Garching, Deutschland, 2016.
[47] E. Rahimzei, K. Sann, and M. Vogel, "Kompendium: Li-Ionen-Batterien Grundlagen, Bewertungskriterien, Gesetze und Normen," DKE, DIN, Jul. 2015.
[48] M. A. Roscher and D. U. Sauer, "Dynamic electric behavior and open-circuit-voltage modeling of LiFePO4-based lithium ion secondary batteries," *J. Power Sources*, vol. 196, no. 1, pp. 331–336, Jan. 2011.
[49] R. Korthauer, Ed., *Handbuch Lithium-Ionen-Batterien*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013.
[50] F. Baronti, M.-Y. Chow, C. Ma, H. Rahimi-Eichi, and R. Saletti, "E-transportation: the role of embedded systems in electric energy transfer from grid to vehicle," *EURASIP J. Embed. Syst.*, vol. 2016, no. 1, Dec. 2016.
[51] J. Warner, *The handbook of lithium-ion battery pack design: chemistry, components, types and terminology*. 2015.
[52] Ashwoods Energy, "Ashwoods Energy - Battery Management Systems," 20-Oct-2016. [Online]. Available: http://ashwoodsenergy.org/battery_management_systems.php. [Accessed: 20-Oct-2016].
[53] AVL, "Battery Management System (BMS) Development - avl.com," 10-Feb-2017. [Online]. Available: https://www.avl.com/battery-management-system-bms-development. [Accessed: 10-Feb-2017].
[54] Delphi Automotive PLC, "Hybrid & Electric Vehicle Products," *Delphi-Media*, 20-Jan-2017. [Online]. Available: http://delphi.com/manufacturers/auto/hevevproducts/controllers/bmc/. [Accessed: 20-Jan-2017].
[55] Elite Power Solutions, "Elite Power Solutions - energy Management Systems," 12-Dec-2016. [Online]. Available: http://elitepowersolutions.com/products/index.php?cPath=44. [Accessed: 12-Dec-2016].
[56] Elithion, "Elithion - Lithiumate," 24-Nov-2016. [Online]. Available: http://elithion.com/lithiumate.php. [Accessed: 24-Nov-2016].
[57] EVPST, "High performance EV BMS with CAN bus& SOC_EV BMS," 23-Dec-2016. [Online]. Available: http://www.evpst.com/ProductShow.asp?ID=119. [Accessed: 23-Dec-2016].
[58] I + ME ACTIA, "I + ME ACTIA - Battery Management Systems," 23-Dec-2016. [Online]. Available: http://www.ime-actia.de/index.php/en/solutions-for-vehicle-manufacturers/solutions-for-cars/battery-management-systems. [Accessed: 23-Dec-2016].
[59] JTT Electronics Ltd., "Battery Management Systems," *JTT Electronics Ltd.-Products*, 20-Jan-2017. [Online]. Available: http://www.jttelectronics.com/products/cat/battery-management-systems. [Accessed: 20-Jan-2017].
[60] Lian Innovative, "Battery Management System, Electric Vehicle, Lifepo4, lithium ion," 23-Dec-2016. [Online]. Available: http://lianinno.com/battery-management-systems/. [Accessed: 23-Dec-2016].
[61] Lithium Balance, "Lithium Balance - LiBAL s-BMS," 24-Nov-2016. [Online]. Available: http://www.lithiumbalance.com/en/component/product/categories/19?sid=37. [Accessed: 24-Nov-2016].
[62] Manzanita Micro, "Manzanita Micro - BMS." [Online]. Available: http://www.manzanitamicro.com/products?page=shop.browse&category_id=22. [Accessed: 09-Jan-2017].
[63] Navitas Solutions, "Wireless Battery Management System for smart grid and electric vehicle applications," *Navitas Solutions-Products & Technologies*, 2016. [Online]. Available: http://www.navitasone.com/. [Accessed: 23-Jan-2017].

[64] Ewert Energy Systems, Inc., "Downloads & Resources \textbar Orion Li-Ion Battery Management System," 15-Dec-2016. [Online]. Available: http://www.orionbms.com/resources/. [Accessed: 15-Dec-2016].
[65] Munro & Associates Inc, "BMW i3 Teardown and Benchmarking Study: Reports Summary and Pricing Detail," Munro & Associates Inc.
[66] Reap Systems, "Reap Systems - Li-Ion Battery Management System (BMS)," 14-Jan-2017. [Online]. Available: http://cgi.ddoerffel.force9.co.uk/_products/products_BMS.html. [Accessed: 14-Jan-2017].
[67] Sensor-Technik Wiedemann GmbH, "mBMS battery management," 24-Nov-2016. [Online]. Available: https://www.sensor-technik.de/en/products.html?view=product&stwpid=14. [Accessed: 24-Nov-2016].
[68] hackaday.io, "Model S BMS hacking," 10-Feb-2017. [Online]. Available: https://hackaday.io/project/10098-model-s-bms-hacking. [Accessed: 10-Feb-2017].
[69] Tritium Pty Ltd., "Tritium » IQ Battery Management System," 24-Dec-2016. [Online]. Available: http://tritium.com.au/products/iq-battery-management-system/. [Accessed: 24-Dec-2016].
[70] Valence, "Battery Management Systems BMS | For Grid And Off Grid Storage," 24-Nov-2016. [Online]. Available: https://www.valence.com/products/battery-management-systems/. [Accessed: 24-Nov-2016].
[71] Ventec-iBMS, "Ventec iBMS 8-18S packs in series," *Ventec-iBMS-Find your BMS*, 20-Jan-2017. [Online]. Available: http://ventec-ibms.com/en/embedded-bms-solutions/ventec-ibms-8-18s-packs-in-series/. [Accessed: 20-Jan-2017].
[72] Altera, "Battery Management System Reference Design - an762.pdf," 10-Feb-2017. [Online]. Available: https://www.altera.com/content/dam/altera-www/global/en_US/pdfs/literature/an/an762.pdf. [Accessed: 10-Feb-2017].
[73] Altera, "Electric Vehicles - Battery Management System," 10-Feb-2017. [Online]. Available: https://www.altera.com/solutions/industry/automotive/applications/electric-vehicles/battery-management-system.html. [Accessed: 10-Feb-2017].
[74] Fraunhofer Institute for Integrated Systems and Device Technology IISB, "fox BMS," 14-Jan-2017. [Online]. Available: https://www.foxbms.org/typo3/index.php?id=foxbms. [Accessed: 14-Jan-2017].
[75] M. Giegerich *et al.*, "Open, flexible and extensible battery management system for lithium-ion batteries in mobile and stationary applications," 2016, pp. 991–996.
[76] LION Smart GmbH, "The smart way to test your batteries.," 14-Feb-2017. [Online]. Available: http://www.lionsmart.com/bms/. [Accessed: 14-Feb-2017].
[77] P. Weicker, "Chapter 5 Architectures," in *A systems approach to lithium-ion battery management*, Boston: Artech House, 2014, p. 59.
[78] D. Andrea, "Chapter 2.3 Topology," in *Battery management systems for large lithium-ion battery packs*, Boston: Artech House, 2010, p. 45.
[79] Battery University, "Types of Lithium-ion Batteries – Battery University," 14-Feb-2017. [Online]. Available: http://batteryuniversity.com/learn/article/types_of_lithium_ion. [Accessed: 14-Feb-2017].
[80] Vera Gebhardt, Gerhard M. Rieger, Jürgen Mottok, and Christian Gießelbach, Eds., *Funktionale Sicherheit nach ISO 26262: ein Praxisleitfaden zur Umsetzung*, 1. Aufl. Heidelberg: dpunkt-Verl, 2013.
[81] "ISO 26262-1: Road vehicles — Functional safety — Part 1 Vocabulary." International Organization for Standardization (ISO), 2011.
[82] Kai Konrad, "Sichere Mikrocontroller im Automobil," *Automobil Elektronik*, pp. 35–37, 02-Jan-2013.
[83] H. Winner, S. Hakuli, F. Lotz, and C. Singer, Eds., *Handbuch Fahrerassistenzsysteme*. Wiesbaden: Springer Fachmedien Wiesbaden, 2015.
[84] Bernd Spanfelner, Detlev Richter, Susanne Ebel, Ulf Wilhelm, Wolfgang Branz, and Carsten Patz, "Challenges in applying the ISO 26262 for driver assistance systems." TUM Media, May-2012.

[85] Bundesministerium der Justiz und für Verbraucherschutz, "Gesetz über die Bereitstellung von Produkten auf dem Markt (Produktsicherheitsgesetz): ProdSG.," 2011. [Online]. Available: http://www.gesetze-im-internet.de/prodsg_2011/BJNR217900011.html#BJNR217900011BJNG000100000. [Accessed: 07-Feb-2017].
[86] Bundesgerichtshof, "Zur Haftung eines Fahrzeugherstellers für die Fehlauslösung von Airbags.," 2009.
[87] H.-L. Ross, *Funktionale Sicherheit im Automobil: ISO 26262, Systemengineering auf Basis eines Sicherheitslebenszyklus und bewährter Managementsysteme*. München: Hanser, 2014.
[88] Ben Bradshaw, "MISRA Guidelines: Automotive Safety Case Arguments.," 18-Jun-2014.
[89] "ISO 26262-3: Road vehicles — Functional safety — Part 3 Concept phase." International Organization for Standardization (ISO), 2011.
[90] D. H. Doughty and C. C. Crafts, "FreedomCAR_Electrical Energy Storage System Abuse Test Manual for Electric and Hybrid Electric Vehicle Applications," Sandia National Laboratories, Albuquerque, New Mexico 87185 and Livermore, California 94550, USA, SAND2005-3123, Aug. 2006.
[91] C. Miedl, "Distributed safety architecture for battery management systems," presented at the ASQF Safety Day 2012, Regensburg, Jul-2012.
[92] M. Henke, "Sicherheitskonzept für Prototypen: Steuergeräte im Automobil," presented at the ASQF Safety Day 2014, Flörsheim bei Frankfurt, Jun-2014.
[93] M. Lienkamp, M. Hammer, and L. Wech, "Funktionale Sicherheit bei Elektrofahrzeugen," *ATZextra*, vol. 19, no. 14, pp. 30–33, Oct. 2014.
[94] W. Taylor, G. Krithivasan, and J. J. Nelson, "System safety and ISO 26262 compliance for automotive lithium-ion batteries," 2012, pp. 1–6.
[95] D. Dürholz, S. Herrmann, S. Kriso, and R. Stärk, *Safety Essentials: ISO 26262 auf einen Blick - kompakt vermittelt*. Kornwestheim: Kugler Maag Cie, 2014.
[96] Martin Schmidt, Marcus Rau, Ekkehard Helmig, and Bernhard Bauer, "Funktionale Sicherheit – Umgang mit Unabhängigkeit, rechtlichen Rahmenbedingungen und Haftungsfragen." Aug-2011.
[97] H. J. Stadlbauer, "Analyse und Test sicherheitskritischer Softwarefunktionen eines Batterie-Management-Systems," Masterarbeit, Technische Universität München, München, 2016.
[98] International Electrotechnical Commission, "IEC 61508: Functional safety of electrical/electronic/ programmable electronic safety-related systems. Sécurité fonctionnelle des systèmes électriques/électroniques électroniques programmables relatifs à la sécurité." International Electrotechnical Commission, 2010.
[99] W. W. Royce, "Managing the development of large software systems: concepts and techniques," presented at the Proceedings of the 9th international conference on Software Engineering, 1987, pp. 328–338.
[100] J. Schäuffele and T. Zurawka, *Automotive Software Engineering*. Wiesbaden: Springer Fachmedien Wiesbaden, 2013.
[101] M. Broy and M. Kuhrmann, *Projektorganisation und Management im Software Engineering*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013.
[102] M. Broy, "Advanced Topics of Software Engineering. Einführende Bemerkungen."
[103] C. Bartelt *et al.*, "V-Modell XT - Das deutsche Referenzmodell für Systementwicklungsprojekte Version: 2.0," Verein zur Weiterentwicklung des V-Modell XT e.V. (Weit e.V.), Bundesverwaltungsamt, Freistaat Bayern, 4Soft GmbH, Airbus Defence & Space AG/GmbH, IABG mbH, Siemens AG, Technische Universität Clausthal, Technische Universität München, 2006.
[104] Kent Beck *et al.*, "Prinzipien hinter dem Agilen Manifest," 2001. [Online]. Available: http://agilemanifesto.org/iso/de/principles.html. [Accessed: 23-Jan-2017].
[105] "ISO 26262-2: Road vehicles — Functional safety — Part 2 Management of functional safety." International Organization for Standardization (ISO), 2011.
[106] "ISO 26262-8: Road vehicles — Functional safety — Part 8 Supporting processes." International Organization for Standardization (ISO), 2011.
[107] "ISO 26262-4: Road vehicles — Functional safety — Part 4 Product development at the system level." International Organization for Standardization (ISO), 2011.

[108] "ISO 26262-5: Road vehicles — Functional safety — Part 5 Product development at the hardware level." International Organization for Standardization (ISO), 2011.
[109] Yevgen Barsukov, "Cell Balancing Using the bq20zxx." Texas Instruments, Jan-2011.
[110] "ISO 26262-6: Road vehicles — Functional safety — Part 6 Product development at the software level." International Organization for Standardization (ISO), 2011.
[111] S. Rudolph, "Struktur- und Funktionsoptimierung der Softwarearchitektur eines Batterie-Management-Systems unter Berücksichtigung der ISO 26262," Masterarbeit, Technische Universität München, München, 2014.
[112] "ISO 26262-9: Road vehicles — Functional safety — Part 9 Automotive Safety Integrity Level (ASIL) oriented and safety-oriented analyses." International Organization for Standardization (ISO), 2011.
[113] H. Kuder *et al.*, "HIS Source Code Metrics." HIS AK Softwaretest, 04-Jan-2008.
[114] "ISO 26262-7: Road vehicles — Functional safety — Part 7 Production and operation." International Organization for Standardization (ISO), 2011.
[115] Axel Dold, "Implementation of Requirements From ISO 26262 in the Development of E/E Components and Systems: Challenges & Approach," presented at the Automotive Electronics and Electrical Systems Forum 2008, 05-Jun-2008.
[116] M. H. Schlummer, "Beitrag zur Entwicklung einer alternativen Vorgehensweise für eine Proven-in-Use-Argumentation in der Automobilindustrie," Doktor Thesis, Bergischen Universität Wuppertal, 2012.
[117] Relecura IP Intelligence Report, "Electric Vehicle (EV) Technology. Battery and charging patents. Tesla Motors vs. the rest.," Sep. 2014.
[118] Google, "Google Patents," *Google Patents*, 23-Dec-2016. [Online]. Available: https://patents.google.com/?q=B60L11%2f1861,B60L11%2f1851,B60L11%2f1864,B60L11%2f1866,B60L11%2f1868,B60L11%2f1874,B60L11%2f1875,B60L11%2f1879&q=G01R31%2f3606,G01R31%2f3662,G01R31%2f3679,G01R31%2f3651,G01R31%2f3655&after=publication:20100101. [Accessed: 23-Dec-2016].
[119] European Patent Office and United States Patents and Trademark Office, "Cooperative Patent Classification. CPC scheme and CPC definitions," 23-Dec-2016. [Online]. Available: http://www.cooperativepatentclassification.org/cpcSchemeAndDefinitions/table.html. [Accessed: 23-Dec-2016].
[120] V. Pop, Ed., *Battery management systems: accurate state-of-charge indication for battery powered applications*. Dordrecht: Springer, 2008.
[121] Y. Zhang, K. K. Shin, X. Tang, and M. A. Salman, "Method and apparatus for estimating soc of a battery," US20120072144, Mar-2012.
[122] A. A. Syed, B. J. Koch, S. Schaefer, and A. Koenekamp, "Band select state of charge weighted scaling method," US20120109556, May-2012.
[123] X. Zhang, X. Tang, J. Lin, Y. Zhang, M. A. Salman, and Y.-K. Chin, "Method for battery capacity estimation," US8084996 B2, 27-Dec-2011.
[124] Anil Paryani, Scott Ira Kohn, Brian Boggs, Andrew David Baglino, and Craig Bruce Carlson, "Battery capacity estimating method and apparatus," US8004243 B2, 23-Aug-2011.
[125] M. W. Verbrugge, E. D. Tate, D. R. Frisch, R. Y. Ying, B. J. Koch, and S. D. Sarbacker, "State of charge method and apparatus," US6639385, Oct-2003.
[126] M. Verbrugge, E. Tate, D. Frisch, and B. Koch, "Method and apparatus for generalized recursive least-squares process for battery state of charge and state of health," US20040162683, Aug-2004.
[127] Xidong Tang, Yandong Zhang, Andrew C Baughman, Brian J. Koch, Jian Lin, and Damon R. Frisch, "Dynamic battery capacity estimation," US8560257 B2, 15-Oct-2013.
[128] Y. Li, "Nonlinear observer for battery state of charge estimation," US8706333, Apr-2014.
[129] Y. Zhang, Kw.-K. Shin, X. Tang, and M. A. Salman, "Method and Apparatus for Estimating Battery Capacity of a Battery.," US8612168B2, 07-Feb-1998.
[130] A. Paryani, "Determining battery DC impedance," US8965721, 24-Feb-2015.
[131] J. Lin, X. Tang, B. J. Koch, D. R. Frisch, and M. J. Gielniak, "Dynamically adaptive method for determining the state of charge of a battery," US7768233, Aug-2010.

[132] Greg Welch and G. Bishop, "An Introduction to the Kalman Filter," University of North Carolina at Chapel Hill, Chapel Hill, USA.
[133] Gregory L. Plett, "State and parameter estimation for an electrochemical cell," US8103485 B2, 24-Jan-2012.
[134] G. L. Plett, "Extended Kalman filtering for battery management systems of LiPB-based HEV battery packs. Part 1. Background.," *J. Power Sources*, vol. 134, no. 2, pp. 252–261, Aug. 2004.
[135] G. L. Plett, "Extended Kalman filtering for battery management systems of LiPB-based HEV battery packs. Part 2. Modeling and identification.," *J. Power Sources*, vol. 134, no. 2, pp. 262–276, Aug. 2004.
[136] G. L. Plett, "Extended Kalman filtering for battery management systems of LiPB-based HEV battery packs. Part 3. State and parameter estimation," *J. Power Sources*, vol. 134, no. 2, pp. 277–292, Aug. 2004.
[137] I. Cho, "Apparatus and method for estimating state of charge of battery using neural network," EP1702219B1, May-2012.
[138] I. Cho, D. Y. Kim, and D. Y. JUNG, "Apparatus and method for estimating state of charge in battery using fuzzy algorithm implemented as neural network," US8626679, Jan-2014.
[139] MarketsAndMarkets, "Battery Management System Market by Battery Type (Lithium-Ion, Advanced Lead-Acid, Flow Battery, & Nickle Battery), Component, Topology (Centralized, Modular, Distributed), Application, and Geography - Global Trend and Forecast to 2022," *MarketsAndMarkets: Top Market Reports*, May-2016. [Online]. Available: http://www.marketsandmarkets.com/Market-Reports/battery-management-bms-market-234498189.html. [Accessed: 01-Feb-2017].
[140] Research in China, "Global and China Power Battery Management System (BMS) Industry Report, 2016-2020," *WhaTech Channel: Energy Market Research*, 16-Aug-2016. [Online]. Available: https://www.whatech.com/market-research/energy/194005-power-battery-management-system-bms-industry-2016-global-market-size-share-growth-and-forecast-to-2020-available-in-new-report. [Accessed: 01-Feb-2017].
[141] Research in China, "Global and China Power Battery Management System (BMS) Industry Report, 2016-2020," *PR Newswire*, 16-Aug-2016. [Online]. Available: http://www.prnewswire.com/news-releases/global-and-china-power-battery-management-system-bms-industry-report-2016-2020-300360357.html. [Accessed: 01-Feb-2017].
[142] Research in China, "Global and China Power Battery Management System (BMS) Industry Report, 2016-2020," *Research in China*, 16-Aug-2016. [Online]. Available: http://www.researchinchina.com/Htmls/Report/2016/10293.html. [Accessed: 19-Jan-2017].
[143] Future Market Insights, "Battery Management System Market: E-Vehicles to be the high value application during forecast period; Global Industry Analysis and Opportunity Assessment, 2015–2025," *Future Market Insights*, 28-Sep-2015. [Online]. Available: http://www.futuremarketinsights.com/reports/battery-management-system-market. [Accessed: 19-Jan-2017].
[144] Research in China, "Power BMS (Battery Management System) Industry 2014-2017 Report for Global and China Markets," *PR Newswire*, 21-Aug-2014. [Online]. Available: http://www.prnewswire.com/news-releases/power-bms-battery-management-system-industry-2014-2017-report-for-global-and-china-markets-272246781.html. [Accessed: 19-Jan-2017].
[145] Research in China, "Power BMS (Battery Management System) Industry 2014-2017 Report for Global and China Markets," *Research in China*, 21-Aug-2014. [Online]. Available: http://www.researchinchina.com/Htmls/Report/2014/7935.html. [Accessed: 19-Jan-2017].
[146] Tom Randall, "Tesla Dominates U.S. Luxury Sedan Sales," *Bloomberg Technology*, 10-Dec-2016. [Online]. Available: https://www.bloomberg.com/news/articles/2016-10-12/tesla-dominates-u-s-luxury-sedan-sales. [Accessed: 19-Jan-2017].
[147] Mobileye N.V., "Lucid Chooses Mobileye as Partner for Autonomous Vehicle Technology," *PR Newswire*, 30-Dec-2016. [Online]. Available: http://www.prnewswire.com/news-releases/lucid-chooses-mobileye-as-partner-for-autonomous-vehicle-technology-300384168.html. [Accessed: 19-Jan-2017].

[148] Faraday Future, "Faraday Future Takes Critical Step Towards Testing Autonomous Vehicles In California," *Faraday Future*, 29-Nov-2016. [Online]. Available: https://www.ff.com/en/media/ff-testing-autonomous-vehicles-in-california/. [Accessed: 19-Jan-2017].
[149] The Tesla Team, "All Tesla Cars Being Produced Now Have Full Self-Driving Hardware," *Tesla*, 19-Oct-2016. [Online]. Available: https://www.tesla.com/blog/all-tesla-cars-being-produced-now-have-full-self-driving-hardware. [Accessed: 19-Jan-2017].
[150] LG Chem., "World's No. 1 automobile battery supplier. Differentiation.," *LG Chem. Product*, 2016. [Online]. Available: http://www.lgchem.com/global/vehicle-battery/car-batteries-Different/product-detail-PDEB0002. [Accessed: 19-Jan-2017].
[151] Sam Abuelsamid, "LG Chem May Be On The Verge Of Dominating EV Battery Industry," *Forbes - Autos*, 28-Oct-2015. [Online]. Available: http://www.forbes.com/sites/samabuelsamid/2015/10/28/lg-chem-may-be-on-the-verge-of-dominating-ev-battery-industry/#5acb6015144d. [Accessed: 19-Jan-2017].
[152] Jay Cole, "LG Chem Says It's Ready To Supply 300 Mile, 120 kWh Batteries," *InsideEVs*, May-2015. [Online]. Available: http://insideevs.com/lg-chem-says-ready-supply-300-mile-120-kwh-batteries/. [Accessed: 19-Jan-2017].
[153] Stephen Edelstein, "LG Chem To Become World's Biggest Electric-Car Battery Supplier? Could Be, Report Says," *Green Car Reports*, 27-Sep-2015. [Online]. Available: http://www.greencarreports.com/news/1099755_lg-chem-to-become-worlds-biggest-electric-car-battery-supplier-could-be-report-says. [Accessed: 19-Jan-2017].
[154] Lee Min-hyung, "LG gears up for new era in auto parts industry," *The Korea Times*, 17-Aug-2016. [Online]. Available: http://m.koreatimes.co.kr/phone/news/view.jsp?req_newsidx=212120. [Accessed: 19-Jan-2017].
[155] Fred Lambert, "Chevy Bolt EV: LG gearing up to 'mass-produce parts' for the car this month," *electrek*, 18-Sep-2016. [Online]. Available: https://electrek.co/2016/08/18/chevy-bolt-ev-lg-mass-produce-parts/?preview_id=22819. [Accessed: 19-Jan-2017].
[156] Eric Loveday, "LG Chem Inks Battery Deal With Tesla," *InsideEVs*, 2016. [Online]. Available: http://insideevs.com/rumor-lg-chem-close-inking-battery-deal-tesla/. [Accessed: 19-Jan-2017].
[157] Mike Ramsey, "Tesla Gets Boost From Korean Battery Maker LG Chem," *The Wall Street Journal*, 28-Oct-2015. [Online]. Available: http://www.wsj.com/articles/tesla-gets-boost-from-korean-battery-maker-lg-chem-1446007554. [Accessed: 19-Jan-2017].
[158] Bridgette LaRose Gollinger, "DENSO Develops Battery Monitoring Unit for Lithium-ion Batteries — Using a proprietary voltage control circuit." DENSO International America, Inc., 01-Nov-2010.
[159] Bridgette LaRose Gollinger, "Hybrid and Electric Vehicle System Technology — DENSO is a Longtime Supplier of Hybrid Vehicle Components." DENSO International America, Inc., 2011.
[160] DENSO Global, "DENSO Develops Battery Monitoring Unit for Lithium-ion Batteries," *DENSO - News Releases*, 01-Dec-2010. [Online]. Available: http://www.globaldenso.com/en/newsreleases/100112-01.html. [Accessed: 19-Jan-2017].
[161] Sara Spezzaferri, "DENSO Develops High Output Power Control Unit and Battery Cooling System for Hybrid Vehicles New Products are Installed on Lexus LS 600h, LS 600hL." DENSO NEWS, 31-May-2007.
[162] DENSO Automotive Systems Australia, "DENSO Develops New Hybrid Vehicle Components," *DENSO Automotive Systems Australia - News Releases*, 04-Apr-2006. [Online]. Available: http://www.denso.com.au/News-Releases/2006/DENSO-Develops-New-Hybrid-Vehicle-Components. [Accessed: 19-Jan-2017].
[163] Preh GmbH, "Intelligent Battery Management in electric and hybrid vehicles," *Preh GmbH – Press Releases*, 06-Apr-2012. [Online]. Available: http://www.preh.com/en/blog/press/intelligent-battery-management-in-electric-and-hybrid-vehicles/. [Accessed: 19-Jan-2017].

[164] Preh GmbH, "Preh to supply i3 with ecus and control systems," *Preh GmbH – Press Releases*, 03-Jun-2014. [Online]. Available: http://www.preh.com/en/blog/press/preh-to-supply-i3-with-ecus-and-control-systems/. [Accessed: 19-Jan-2017].
[165] Christoph Hammerschmidt, "BMW selects Preh to supply HEV battery management system," *EETimes Europe Automotive*, 06-Nov-2012. [Online]. Available: http://www.automotive-eetimes.com/news/bmw-selects-preh-supply-hev-battery-management-system. [Accessed: 19-Jan-2017].
[166] Götz Fuchslocher, "Preh stellt neues 48V-Batteriemanagement vor," *Automobil Produktion*, 22-Sep-2015. [Online]. Available: https://www.automobil-produktion.de/technik-produktion/fahrzeugtechnik/preh-stellt-neues-48v-batteriemanagement-vor-254.html. [Accessed: 19-Jan-2017].
[167] Preh GmbH, "Preh presents battery management technology for 48 volt systems at iaa 2015," *Preh GmbH – Press Releases*, 15-Sep-2015. [Online]. Available: http://www.preh.com/en/blog/allgemein-en/preh-presents-battery-management-technology-for-48-volt-systems-at-iaa-2015/. [Accessed: 19-Jan-2017].
[168] Jerry Garrett, "Toyota and Tesla Trot Out the RAV4 EV," *Wheels - The New York Times*, 08-Mar-2012. [Online]. Available: https://wheels.blogs.nytimes.com/2012/08/03/toyota-and-tesla-trot-out-the-rav4-ev/?ref=automobiles&_r=2. [Accessed: 19-Jan-2017].
[169] Tesla Updates, "Elon Musk thanks Daimler and Toyota for bailing Tesla out," *Tesla Updates*, 06-Mar-2016. [Online]. Available: http://www.teslaupdates.co/2016/06/elon-musk-thanks-daimler-and-toyota-for.html. [Accessed: 19-Jan-2017].
[170] Continental AG, "Continental starts series production of lithium-ion batteries for hybrid vehicles," *Continental AG - Press Portal*, 24-Sep-2008. [Online]. Available: http://www.continental-corporation.com/www/pressportal_com_en/themes/press_releases/3_automotive_group/powertrain/press_releases/pr_2008_09_24_liion_batteries_en.html. [Accessed: 19-Jan-2017].
[171] Continental AG, "Start of Production for 48-Volt Hybrid Modular System from Continental," *Continental AG - Press Portal*, 20-Oct-2016. [Online]. Available: http://www.continental-corporation.com/www/pressportal_com_en/themes/press_releases/3_automotive_group/powertrain/press_releases/pr_2016_10_20_48_volt_start_trade_en.html. [Accessed: 19-Jan-2017].
[172] Wikipedia, the free encyclopedia, "Hyundai Tucson," *Wikipedia, the free encyclopedia*, 2017. [Online]. Available: https://en.wikipedia.org/wiki/Hyundai_Tucson#Second_generation_.282009.E2.80.93present.29. [Accessed: 19-Jan-2017].
[173] Navigant Research, "LG Chem and Samsung SDI Score Highest in Navigant Research Assessment of Lithium Ion Battery Manufacturers," *Navigant Research - Press Releases*, 2015. [Online]. Available: https://www.navigantresearch.com/newsroom/lg-chem-and-samsung-sdi-score-highest-in-navigant-research-assessment-of-lithium-ion-battery-manufacturers. [Accessed: 19-Jan-2017].
[174] Navigant Research, "LG Chem, Panasonic, and Samsung SDI Score Highest in Assessment of Lithium Ion Battery Manufacturers," *Navigant Research - Press Releases*, 2015. [Online]. Available: https://www.navigantresearch.com/newsroom/lg-chem-panasonic-and-samsung-sdi-score-highest-in-assessment-of-lithium-ion-battery-manufacturers. [Accessed: 19-Jan-2017].
[175] Navigant Research, "Navigant Research Leaderboard Report: Li-Ion Grid Storage," *Navigant Research - Press Releases*, 2015. [Online]. Available: http://www.navigantresearch.com/research/navigant-research-leaderboard-report-li-ion-grid-storage. [Accessed: 19-Jan-2017].
[176] Navigant Research, "Navigant Research Leaderboard Report: Lithium Ion Batteries for Transportation," *Navigant Research - Press Releases*, 2015. [Online]. Available: https://www.navigantresearch.com/research/navigant-research-leaderboard-report-lithium-ion-batteries-for-transportation. [Accessed: 19-Jan-2017].
[177] David Sedgwick, "Top 100 global OEM parts suppliers in 2013," *Automotive News*, vol. Supplement, 17-Jun-2013.

[178] David Sedgwick, "Top 100 global OEM parts suppliers in 2014," *Automotive News*, vol. Supplement, 15-Jun-2015.
[179] David Sedgwick, "Top 100 global OEM parts suppliers in 2015," *Automotive News*, vol. Supplement, 20/06/02016.
[180] David Sedgwick, "More vehicle electrification expected to juice demand for more powerful systems," *Automotive News*, 04-Nov-2016.
[181] Delphi Automotive PLC, "Closing Fuel/CO2 regulation gaps with 48-volt, mild hybrids," *Delphi-Media*, 20-Jan-2017. [Online]. Available: http://delphi.com/media/feature-stories/Details/closing-fuel-co2-regulation-gaps-with-48-volt-mild-hybrids. [Accessed: 20-Jan-2017].
[182] Doron Levin, "Delphi Wants Your Old Car Engine to Become a Hybrid," *The Street*, 16-May-2016. [Online]. Available: https://www.thestreet.com/story/13573304/1/delphi-wants-your-car-battery-to-go-hybrid.html. [Accessed: 20-Jan-2017].
[183] Greg Gardner, "Delphi bets on a new, 48-volt system as cars' electrical needs grow," *Detroit Free Press*, 16-May-2016. [Online]. Available: http://www.freep.com/story/money/cars/2016/05/16/delphi-bets-new-48-volt-system-cars-electrical-needs-grow/84454686/. [Accessed: 20-Jan-2017].
[184] Greg Gardner, "Delphi 48-volt technology will be in new cars by 2017," *Detroit Free Press*, 14-Apr-2016. [Online]. Available: http://www.freep.com/story/money/cars/2016/04/13/delphi-48-volt-technology-new-cars-2017/82949374/. [Accessed: 20-Jan-2017].
[185] Hartmut Schneeweiss, "Continental on overcoming the challenges for hybrid and electric vehicles," 2017.
[186] James M. Amend, "Delphi Wants Partners for 48V Technology," *WardsAuto*, 18-May-2016. [Online]. Available: http://wardsauto.com/engines/delphi-wants-partners-48v-technology. [Accessed: 20-Jan-2017].
[187] Greg Gardner and Chris Woodyard, "Automakers juice up cars' electrical systems to add tech," *USA Today*, 17-Jun-2016. [Online]. Available: http://www.usatoday.com/story/money/cars/2016/05/17/automakers-juice-up-cars-electrical-systems-new-tech/84491888/. [Accessed: 20-Jan-2017].
[188] Jack Stewart, "The German Auto Industry Is Finally (Maybe) Done With Gas," *Wired*, 18-Oct-2016. [Online]. Available: https://www.wired.com/2016/10/german-auto-industry-finally-maybe-done-gas/. [Accessed: 20-Jan-2017].
[189] Preh GmbH, "Preh and Joyson sign letter of intent to form a joint venture," *Preh GmbH – Press Releases*, 20-Aug-2010. [Online]. Available: http://www.preh.com/en/blog/press/preh-and-joyson-sign-letter-of-intent-to-form-a-joint-venture/. [Accessed: 20-Jan-2017].
[190] Preh GmbH, "Joyson and Preh forge a high-growth technology company in the automotive sector," *Preh GmbH – Press Releases*, 04-Aug-2011. [Online]. Available: http://www.preh.com/en/blog/press/joyson-and-preh-forge-a-high-growth-technology-company-in-the-automotive-sector/. [Accessed: 20-Jan-2017].
[191] Preh GmbH, "Preh supplies the interior control system for the Chevrolet Equinox," *Preh GmbH – Press Releases*, 10-Feb-2009. [Online]. Available: http://www.preh.com/en/blog/press/preh-supplies-the-interior-control-system-for-the-chevrolet-equinox/. [Accessed: 20-Jan-2017].
[192] Preh GmbH, "Preh supplies the electronic climate control unit for Ford Taurus and Flex," *Preh GmbH – Press Releases*, 07-Oct-2009. [Online]. Available: http://www.preh.com/en/blog/press/preh-supplies-the-electronic-climate-control-unit-for-ford-taurus-and-flex/. [Accessed: 20-Jan-2017].
[193] Preh GmbH, "2013 Ford Fusion now with preh integrated center stack," *Preh GmbH – Press Releases*, 11-May-2012. [Online]. Available: http://www.preh.com/en/blog/press/2013-ford-fusion-now-with-preh-integrated-center-stack/. [Accessed: 20-Jan-2017].
[194] Preh GmbH, "2013 Cadillac XTS and ats to get Preh climate control modules," *Preh GmbH – Press Releases*, 20-Apr-2013. [Online]. Available: http://www.preh.com/en/blog/press/2013-cadillac-xts-and-ats-to-get-preh-climate-control-modules/. [Accessed: 20-Jan-2017].
[195] Preh GmbH, "Preh's center console concept technologies are now in series production," *Preh GmbH – Press Releases*, 20-Apr-2013. [Online]. Available:

http://www.preh.com/en/blog/press/prehs-center-console-concept-technologies-are-now-in-series-production/. [Accessed: 20-Jan-2017].
[196] Preh GmbH, "Preh control system for the iconic subcompact," *Preh GmbH – Press Releases*, 28-May-2014. [Online]. Available: www.preh.com/en/blog/press/preh-control-system-for-the-iconic-subcompact/. [Accessed: 20-Jan-2017].
[197] Preh GmbH, "Preh climate control system in the new Audi TT," *Preh GmbH – Press Releases*, 13-Aug-2014. [Online]. Available: http://www.preh.com/en/blog/aktuelles-en/preh-climate-control-system-in-the-new-audi-tt/. [Accessed: 20-Jan-2017].
[198] Preh GmbH, "Preh innovative premium center console featured on Porsche 918 Spyder," *Preh GmbH – Press Releases*, 21-Apr-2015. [Online]. Available: http://www.preh.com/en/blog/press/preh-innovative-premium-center-console-featured-on-porsche-918-spyder/. [Accessed: 20-Jan-2017].
[199] Wikipedia, the free encyclopedia, "Venturi Automobiles," *Wikipedia, the free encyclopedia*, 2016. [Online]. Available: https://en.wikipedia.org/wiki/Venturi_Automobiles. [Accessed: 20-Jan-2017].
[200] Wikipedia, the free encyclopedia, "Voxan," *Wikipedia, the free encyclopedia*, 2012. [Online]. Available: https://en.wikipedia.org/wiki/Voxan. [Accessed: 20-Jan-2017].
[201] Pascal Rabiller, "Mérignac : Ventec élève l'intelligence en batteries," *La Tribune*, 01-May-2015. [Online]. Available: http://objectifaquitaine.latribune.fr/innovation/2015-01-05/merignac-ventec-eleve-l-intelligence-en-batteries.html. [Accessed: 20-Jan-2017].
[202] Société, "VENTEC. Fiche entreprise : chiffres d'affaires, bilan et résultat," *Société*, 20-Jan-2017. [Online]. Available: http://www.societe.com/societe/ventec-514332576.html. [Accessed: 20-Jan-2017].
[203] Ventec-iBMS, "Ventec-Intelligent Battery Management System. History.," *Ventec-iBMS-History*, 20-Jan-2017. [Online]. Available: http://ventec-ibms.com/en/history/. [Accessed: 20-Jan-2017].
[204] Ventec-iBMS, "Ventec iBMS 8-16S packs in parallel," *Ventec-iBMS-Find your BMS*, 20-Jan-2017. [Online]. Available: http://ventec-ibms.com/en/embedded-bms-solutions/ventec-ibms-8-16s-packs-in-parallel/. [Accessed: 20-Jan-2017].
[205] Ventec-iBMS, "Ventec iBMS 10S 50-20," *Ventec-iBMS-Find your BMS*, 20-Jan-2017. [Online]. Available: http://ventec-ibms.com/en/embedded-bms-solutions/ventec-ibms-10s-50-20-en/. [Accessed: 20-Jan-2017].
[206] Ventec-iBMS, "Unique and high level of quality for our stationary solutions," *Ventec-iBMS-History*, 20-Jan-2017. [Online]. Available: http://ventec-ibms.com/en/our-bms-solutions/stationary-solutions/. [Accessed: 20-Jan-2017].
[207] Ventec-iBMS, "A new concept is born for electric bicycles," *Ventec-iBMS-Blog*, 20-Jan-2017. [Online]. Available: http://ventec-ibms.com/en/electric-bicycles/. [Accessed: 20-Jan-2017].
[208] Aidia Lopez, "Venturi Fetish (2010) Part 1: Car," *Cboas*, 25-Sep-2016. [Online]. Available: https://www.cboas.com/venturi-fetish-2010-part-1/. [Accessed: 20-Jan-2017].
[209] Wikipedia, the free encyclopedia, "Frazer Nash," *Wikipedia, the free encyclopedia*, 2016. [Online]. Available: https://en.wikipedia.org/wiki/Frazer_Nash. [Accessed: 20-Jan-2017].
[210] Wikipedia, the free encyclopedia, "Kamkorp," *Wikipedia, the free encyclopedia*, 2016. [Online]. Available: https://en.wikipedia.org/wiki/Kamkorp. [Accessed: 20-Jan-2017].
[211] Kamkorp Group, "Kamkorp Group Website," 20-Jan-2017. [Online]. Available: http://www.kamkorp.com/. [Accessed: 20-Jan-2017].
[212] Frazer-Nash, "Frazer-Nash Energy Systems. Website," 20-Jan-2017. [Online]. Available: http://www.fn-energy.com/. [Accessed: 20-Jan-2017].
[213] Frazer-Nash, "Frazer-Nash Research Ltd. Website," 20-Jan-2017. [Online]. Available: http://www.frazer-nash.com/. [Accessed: 20-Jan-2017].
[214] JTT Electronics Ltd., "JTT Electronics Announces Strategic Partnership with GIO Motors," *JTT Electronics Ltd.-News*, 2010. [Online]. Available: http://www.jttelectronics.com/pages/jtt-electronics-partnership-with-gio-motors.php. [Accessed: 20-Jan-2017].
[215] JTT Electronics Ltd., "JTT Electronics Ltd. Website," *JTT Electronics Ltd.-Home*, 20-Jan-2017. [Online]. Available: http://www.jttelectronics.com/pages/about-us.php. [Accessed: 20-Jan-2017].

[216] JTT Electronics Ltd., "JTT Involved in WWU hybrid bus project," *JTT Electronics Ltd.-News*, 20-Jan-2017. [Online]. Available: http://www.jttelectronics.com/pages/wwu-and-jtt-hybrid-bus-project.php. [Accessed: 20-Jan-2017].
[217] Lithium Balance A/S, "Lithium Balance A/S - Our history," *Lithium Balance A/S - Our history*, 2016. [Online]. Available: http://www.lithiumbalance.com/en/company/our-history. [Accessed: 21-Jan-2017].
[218] OXIS ENERGY and Lithium Balance A/S, "OXIS ENERGY Battery Systems headed for China," *Press release*, 06-Aug-2016. [Online]. Available: http://www.lithiumbalance.com/images/attachments/news/LithiumSulfurPressRelease.pdf. [Accessed: 21-Jan-2017].
[219] Ventec-iBMS, "Ventec develops its sales for EAB," *Ventec-iBMS-Blog*, 20-Jan-2017. [Online]. Available: http://ventec-ibms.com/en/ventec-develops-its-sales-for-eab/. [Accessed: 20-Jan-2017].
[220] Sensor-Technik Wiedemann GmbH, "Partnership between the companies ERNI and STW in the application of Power Boards." Sensor-Technik Wiedemann GmbH, Jul-2015.
[221] Sensor-Technik Wiedemann GmbH, "Sensor-Technik Wiedemann introduces the 40 kW powerMELA electric drive." Sensor-Technik Wiedemann GmbH, Nov-2014.
[222] Sensor-Technik Wiedemann GmbH, "Krone awards STW 'Supplier of the Year.'" Sensor-Technik Wiedemann GmbH, Oct-2015.
[223] Sensor-Technik Wiedemann GmbH, "ElringKlinger AG to partner with Sensor-Technik Wiedemann GmbH." Sensor-Technik Wiedemann GmbH, Apr-2016.
[224] Sensor-Technik Wiedemann GmbH, "New Battery Management System Generation mBMS by STW." Sensor-Technik Wiedemann GmbH, Apr-2016.
[225] Sensor-Technik Wiedemann GmbH, "Partnership between Sensor -Technik Wiedemann and Cumulocity." Sensor-Technik Wiedemann GmbH, Jul-2015.
[226] Sensor-Technik Wiedemann GmbH, "Sensor-Technik Wiedemann (STW), Member of the Ethernet POWERLINK Standardization Group (EPSG)." Sensor-Technik Wiedemann GmbH, Nov-2015.
[227] Sensor-Technik Wiedemann GmbH, "STW introduces new platforms for the „Cloud of Things" by Deutsche Telekom." Sensor-Technik Wiedemann GmbH, Nov-2015.
[228] Sensor-Technik Wiedemann GmbH, "STW offers measuring in the cloud." Sensor-Technik Wiedemann GmbH, Apr-2016.
[229] Sensor-Technik Wiedemann GmbH, "Mobile machines made cloud capable by STW." Sensor-Technik Wiedemann GmbH, Nov-2016.
[230] Lithium Balance A/S, "Lithium Balance-Battery Management Systems. Case Study. Lithium Balance's lithium ion Battery solution for Toyota Materian Handling Applications." Lithium Balance A/S, 20-May-2011.
[231] Navitas Systems, "Navitas Systems Forges Unique Offering in Lithium-Ion Battery Development for Class 1 and Class 2 Forklift Trucks," *Navitas Systems-News & Events*, 15-Sep-2015. [Online]. Available: http://www.navitassys.com/2015/09/14/navitas-systems-forges-unique-offering-in-lithium-ion-battery-development-for-class-1-and-class-2-forklift-trucks/. [Accessed: 22-Jan-2017].
[232] Paul Crompton, "Growing lithium trend threatens to usurp lead-acid," *Energy Storage Publishing*, 07-Aug-2016. [Online]. Available: http://www.bestmag.co.uk/content/growing-lithium-trend-threatens-usurp-lead-acid?utm_source=CIBF+2016&utm_campaign=137934ba56-Best_Battery_Briefing_14_03_163_11_2016&utm_medium=email&utm_term=0_7b3b2075b0-137934ba56-406223257. [Accessed: 22-Jan-2017].
[233] New York Battery and Energy Storage, "Navitas Systems Member Spotlight," *New York Battery and Energy Storage*, 22-Jan-2017. [Online]. Available: http://www.ny-best.org/page/navitas-systems-member-spotlight. [Accessed: 22-Jan-2017].
[234] Navitas Systems, "Navitas Systems Announces Award to Deploy StarlifterTM Lithium Forklift Batteries at Major Defense Logistics Agency (DLA) Location," *Navitas Systems-News & Events*, 12-May-2016. [Online]. Available: http://www.navitassys.com/2016/12/05/navitas-systems-

announces-award-to-deploy-starliftertm-lithium-forklift-batteries-at-major-defense-logistics-agency-dla-location/. [Accessed: 22-Jan-2017].
[235] Navitas Systems-Partners, "Navitas Systems Partners," *Navitas Systems Partners*, 2013. [Online]. Available: http://www.navitassys.com/about-us/partners/. [Accessed: 22-Jan-2017].
[236] Raymond Barrett and David Baumann, "Supply chain concerns rejected in CFIUS review of A123," *Financial Times*, 02-Dec-2013. [Online]. Available: http://www.ft.com/cms/s/2/aae37526-7559-11e2-b8ad-00144feabdc0.html?ft_site=falcon&desktop=true#axzz2KoRrxMes. [Accessed: 22-Jan-2017].
[237] Amanda Roraff, John Roach, and Amanda Tomasek, "Detroit Ambulance Fleet to Lead the Nation in Going Green," *Navitas Systems-News & Events*, 15-Sep-2015. [Online]. Available: http://www.navitassys.com/wp-content/uploads/2015/09/CityofDetroit_Navitas_NextEnergy_APU_FINAL_2015.09.15.pdf. [Accessed: 22-Jan-2017].
[238] Laura Varriale, "Navitas reveals lithium battery line as drop-in lead-acid replacement," *Energy Storage Publishing*, 17-Sep-2014. [Online]. Available: http://www.bestmag.co.uk/content/navitas-reveals-lithium-battery-line-drop-lead-acid-replacement?utm_source=Advertisers+-+non+Chinese&utm_campaign=3abc192b48-BBB_22_09_TEST9_19_2014&utm_medium=email&utm_term=0_ca2d533884-3abc192b48-406086773. [Accessed: 22-Jan-2017].
[239] REAP Systems, "Hybrid Swimmer Delivery Vehicle," *REAP Systems-Case Studies*, 2016. [Online]. Available: http://www.reapsystems.co.uk/hybrid-swimmer-delivery-vehicle-battery-system. [Accessed: 23-Jan-2017].
[240] Maritime Journal, "Dennis Doerffel: REAP Systems," *Maritime Journal*, 02-Feb-2016.
[241] REAP Systems, "REAP Systems-News 2005-2007," *REAP Systems-News*, 2016. [Online]. Available: http://www.reapsystems.co.uk/in-the-press-2005-2007/. [Accessed: 23-Jan-2017].
[242] REAP Systems, "Battery Systems for Underwater Vehicles," *REAP Systems-Case Studies*, 2009. [Online]. Available: http://cgi.ddoerffel.force9.co.uk/_case_studies/underwatervehicles.html. [Accessed: 23-Jan-2017].
[243] Venture Magazine, "Technology for a changing world," *Venture Magazine*, pp. 61–62, May-2007.
[244] GREEN4SEA, "Project Venice to embrace electric power," *GREN4SEE-Technology*, 21-Apr-2016. [Online]. Available: http://www.green4sea.com/project-venice-to-embrace-electric-power/. [Accessed: 23-Jan-2017].
[245] Maritime Journal, "Hybrid 'drop-in' could break industry hold up," *Maritime Journal*, 04-Jul-2016.
[246] Maritime Journal, "Hybrid 'cookbook' for smaller yards," *Maritime Journal*, 10-May-2015.
[247] Richard Tyler, "Millbrook Technology Campus in Southampton: an incubator full of surprises," *The Telegraph Online*, 02-Aug-2010.
[248] REAP Systems, "650V Battery Management System," *REAP Systems-Case Studies*, 2009. [Online]. Available: http://cgi.ddoerffel.force9.co.uk/_case_studies/650vBMS.html. [Accessed: 23-Jan-2017].
[249] Lian Innovative, "Underwater robotics," *Lian Innovative-Markets*, 2015. [Online]. Available: http://lianinno.com/markets/. [Accessed: 23-Jan-2017].
[250] Wikipedia, the free encyclopedia, "Formula E," *Wikipedia, the free encyclopedia*, 2015. [Online]. Available: https://en.wikipedia.org/wiki/Formula_E. [Accessed: 23-Jan-2017].
[251] Gregory Offer, Raj Shah, Benjamin Smith, Billy Wu, and Alexander Schey, "Fuel for thought," *Annual Showcase 2010-Imperial College*, pp. 054–058, 2010.
[252] Gregory Offer, Raj Shah, Benjamin Smith, Billy Wu, and Alexander Schey, "Racing Green," *University Focus: Imperial College*, pp. 67–72, 2010.
[253] Ventec-iBMS, "Speed record of the electric vehicule: VBB-3," *Ventec-iBMS-News*, 2013. [Online]. Available: http://ventec-ibms.com/en/speed-record-of-the-electric-vehicule-vbb-3/. [Accessed: 12-May-2016].

[254] Ventec-iBMS, "World speed record for electric vehicles in 2013 and VBB-3," *Ventec-iBMS-News*, 2013. [Online]. Available: http://ventec-ibms.com/en/world-speed-record-vbb-3/. [Accessed: 23-Jan-2017].
[255] Ventec-iBMS, "Ventec, partner of the solar-powered car Eco Solar Breizh," *Ventec-iBMS-News*, 15-Nov-2014. [Online]. Available: http://ventec-ibms.com/en/ventec-partner-solar-powered-car-eco-solar-breizh/. [Accessed: 20-Jan-2017].
[256] Ventec-iBMS, "Abu Dhabi Solar Challenge – Part 2," *Ventec-iBMS-News*, 13-Jan-2015. [Online]. Available: http://ventec-ibms.com/en/abu-dahbi-solar-challenge-part-2/. [Accessed: 20-Jan-2017].
[257] REAP Systems, "Battery Systems for UCL Solar Car," *REAP Systems-Case Studies*, 2007. [Online]. Available: http://cgi.ddoerffel.force9.co.uk/_case_studies/ulc_solar_car.html. [Accessed: 23-Jan-2017].
[258] Stefano Eleuteri, "Panorama: World Solar Challenge," *PHOTON*, Nov-2007.
[259] Stephanie Pielot, "Long live the Li-ion King! Another win for Nuon in Australia," *REAP Systems-News*, 11-Mar-2015. [Online]. Available: http://www.reapsystems.co.uk/news/2015/11/2/nuon-win-world-solar-challenge-2015. [Accessed: 23-Jan-2017].
[260] TU Delft, "Nuon Solar Team," *TU Delft-Teams*, 23-Jan-2017. [Online]. Available: http://ddream.tudelft.nl/en/teams/nuon-solar-team/. [Accessed: 23-Jan-2017].
[261] Tritium Pty Ltd., "Brisbane Technology Supports Winners of WSC," *Tritium Pty Ltd.-Press releases*, 19-Oct-2013. [Online]. Available: http://tritium.com.au/about-us/press-releases/brisbane-technology-supports-winners-of-world-solar-challenge/. [Accessed: 23-Jan-2017].
[262] Tritium Pty Ltd., "Testimonials," *Tritium Pty Ltd.-Press releases*, 23-Jan-2017. [Online]. Available: http://tritium.com.au/about-us/testimonials/. [Accessed: 23-Jan-2017].
[263] Tritium Pty Ltd., "Solar car racing," *Tritium Pty Ltd.-Press releases*, 2013. [Online]. Available: http://tritium.com.au/solar-car-racing/. [Accessed: 23-Jan-2017].
[264] Tritium Pty Ltd., "Veefil Launch," *Tritium Pty Ltd.-Press releases*, 23-Jan-2017. [Online]. Available: http://tritium.com.au/about-us/press-releases/new-technology-developed-by-an-australian-company-to-bring-the-future-of-electric-vehicles-evs-one-step-closer/. [Accessed: 23-Jan-2017].
[265] Tritium Pty Ltd., "Innovative engineering firm in the fast lane," *Tritium Pty Ltd.-Press releases*, 10-Nov-2013. [Online]. Available: http://tritium.com.au/about-us/press-releases/innovative-engineering-firm-in-the-fast-lane-to-success/. [Accessed: 23-Jan-2017].
[266] Sam Parkinson, "Australian EV fast charger wins top automotive, transport award," *Reneweconomy*, 30-May-2014.
[267] Wallstreet online, "Australia's Tritium announces international collaboration with major Chinese manufacturer at Intersolar 2014 / Veefil® Electric Vehicle Fast Charger makes European debut at Intersolar 2014 Stand No," *Walstreet online*, 06-May-2014. [Online]. Available: http://www.wallstreet-online.de/nachricht/6804512-australia-39-s-tritium-announces-international-collaboration-with-major-chinese-manufacturer-at-intersolar-2014-veefil-electric-vehicle-charger-makes-european-debut-at-intersolar-2014-stand-no-b3-670b. [Accessed: 23-Jan-2017].
[268] Sophie Vorrath, "Oz EV fast charger debuts in Europe, in new distribution deal," *Reneweconomy*, 06-May-2014.
[269] Jasmina, "Australian electric vehicle fast charger targets global markets," *Australian Manufacturing*, 06-Sep-2014.
[270] Electric Cars Report, "Germany-based E-WALD to Market Veefil Electric Vehicle Fast Charger," 20-Oct-2014. [Online]. Available: http://electriccarsreport.com/2014/10/germany-based-e-wald-market-veefil-electric-vehicle-fast-charger/. [Accessed: 23-Jan-2017].
[271] automotive FLEET, "Australian EV Charging Specialist Comes to Germany," *automotive FLEET*, 20-Oct-2014.
[272] Sophie Vorrath, "Qld-made EV fast charging technology wins EU supply deal," *Reneweconomy*, 20-Oct-2014.

[273] Sophie Vorrath, "Australian EV fast charger heads for North American market," *Reneweconomy*, 07-Aug-2014.
[274] Sophie Foster, "Tritium banks on growth surge off one of world's fastest electric vehicle charging stations," *The Courier Mail*, 07-Sep-2014.
[275] Energy Busines News, "Qld EV battery charger gets US/Canada greenlight," *Energy Busines News*, 07-Sep-2014.
[276] Christopher DeMorro, "Australia's Veefil EV Charger Comes To America," *EV Obsession*, 20-Jun-2014. [Online]. Available: http://evobsession.com/australias-veefil-ev-charger-comes-america/. [Accessed: 23-Jan-2017].
[277] Jasmina, "Tritium partners with ChargePoint to spread its electric vehicle fast charging technology across the US," *Australian Manufacturing*, 04-Jan-2015.
[278] Green Car Congress, "Tritium and ChargePoint partner for fast charging across the US," 26-Mar-2015. [Online]. Available: http://www.greencarcongress.com/2015/03/20150326-tritium.html. [Accessed: 23-Jan-2017].
[279] ChargePoint, "Tritium and ChargePoint Partner for Fast Charging Across the U.S.," *ChargePoint-News & Updates*, 23-Jan-2017. [Online]. Available: https://www.chargepoint.com/about/news/tritium-and-chargepoint-partner-fast-charging-across-us/. [Accessed: 23-Jan-2017].
[280] Clean Power Auto LLC, "Clean Power Auto LLC Portal," *About Clean Power Auto LLC*, 23-Jan-2017. [Online]. Available: http://cleanpowerauto.com/. [Accessed: 23-Jan-2017].
[281] Lithium Balance A/S, "Lithium Balance-Battery Management Systems. Case Study. The high speed electric vehicle." Lithium Balance A/S, Nov-2009.
[282] Lithium Balance A/S, "Lithium Balance-Battery Management Systems. Case Study. A passion for quality." Lithium Balance A/S, 06-Mar-2011.
[283] Sensor-Technik Wiedemann GmbH, "Optimum efficiency through power electrification." Sensor-Technik Wiedemann GmbH, Nov-2015.
[284] Sensor-Technik Wiedemann GmbH, "E-Mobility for mobile machines." Sensor-Technik Wiedemann GmbH, Apr-2016.
[285] Tritium Pty Ltd., "Electric Holden Commodore," *Tritium Pty Ltd.-Press releases*, 23-Jan-2017. [Online]. Available: http://tritium.com.au/electric-holden-commodore/. [Accessed: 23-Jan-2017].
[286] University of Southampton, "Car of the future now in Sothampton," *Bulletin-the weekly newspaper of the University of Southampton*, Mar-2003.
[287] Max Glaskin, "IDEA PARADE," *Auto Express*, 22-Oct-2003.
[288] James M. Amend, "Delphi's 48V Bet Feels Like Sure Thing," *WardsAuto*, 07-Dec-2016. [Online]. Available: http://wardsauto.com/technology/delphi-s-48v-bet-feels-sure-thing. [Accessed: 23-Jan-2017].
[289] Continental AG, "Continental Drives 'Electrification tailored to fit' from Stop-Start Systems to Fully Electric Vehicles," *Continental AG - Press Portal*, 07-Mar-2013. [Online]. Available: http://www.continental-corporation.com/www/pressportal_com_en/themes/press_releases/3_automotive_group/powertrain/press_releases/pr_2013_07_03_elecrification_tailored_to_fit_en.html. [Accessed: 23-Jan-2017].
[290] Continental AG, "Giving Engines a Break: Continental's '48-Volt Eco Drive' Technology Significantly Reduces Fuel Consumption," *Continental AG - Press Portal*, 11-Dec-2014. [Online]. Available: http://www.continental-corporation.com/www/pressportal_com_en/themes/press_releases/3_automotive_group/powertrain/press_releases/pr_2014_11_12_48_volt_vox_en.html. [Accessed: 23-Jan-2017].
[291] Davide Andrea, "Elithion products in the real world," *Elithion Applications*, 23-Jan-2017. [Online]. Available: http://www.elithion.com/applications.php. [Accessed: 23-Jan-2017].
[292] Manzanita Micro Power Systems, "Manzanita Micro Power Systems - About us.," *About us*, 2011. [Online]. Available: http://www.manzanitamicro.com/about-us. [Accessed: 23-Jan-2017].
[293] Yuan Dao and William Jeffrey Schlanger, "Wireless Battery Management System," US 2015/0188334 A1, 07-Feb-2015.

[294] J. Farmer *et al.*, "Wireless Battery Management System for Safe High-Capacity Li-Ion Energy Storage," 01-Aug-2013.
[295] Electronic Engineering Journal, "Linear Technology Demonstrates Breakthrough Wireless Battery Management System in BMW i3 at CES," *Electronic Engineering Journal-Industry News*, 01-Apr-2017. [Online]. Available: http://www.eejournal.com/archives/news/20170104-01/. [Accessed: 23-Jan-2017].
[296] Hermann Straubinger, "World's first wireless car battery management system," *electronica 2016*, 11-Oct-2016. [Online]. Available: http://blog.electronica.de/en/2016/11/10/electronica-2016-worlds-first-wireless-car-battery-management-system/. [Accessed: 23-Jan-2017].
[297] Jaesik Lee, Inseop Lee, Minkyu Lee, and Andrew M. Chon, "Wireless battery area network for a smart battery management system," US9,293,935, 22-Mar-2016.
[298] Lithium Balance A/S, "ISO 9001 Certification," *Lithium Balance A/S - News*, 10-Jul-2015. [Online]. Available: http://www.lithiumbalance.com/en/support-2/news/35-other-news/3-iso-9001-certification. [Accessed: 23-Jan-2017].
[299] Lithium Balance A/S, "Green Smiley," *Lithium Balance A/S - News*, 15-Oct-2015. [Online]. Available: http://www.lithiumbalance.com/en/support-2/news/35-other-news/5-green-smiley. [Accessed: 23-Jan-2017].
[300] K. Vestin, "n-BMS, a novel ISO26262 compliant battery management system," presented at the 28th International Electric Vehicle Symposium and Exhibition EVS28, Goyang, Korea, 05-Mar-2015.
[301] Sensor-Technik Wiedemann GmbH, "On the safe side long-term with the IEC 61508." Sensor-Technik Wiedemann GmbH, May-2016.
[302] ACTIA Group, "ACTIA expands the electric drive range," *ACTIA Group-News*, Jul-2016. [Online]. Available: http://actia.com/en/press/news/item/ACTIA-expands-the-electric-drive-range. [Accessed: 23-Jan-2017].
[303] Intersil, "Automotive Battery Management Solutions (BMS)," *Intersil-All Products*, 23-Jan-2017. [Online]. Available: http://www.intersil.com/en/products/end-market-specific/automotive-ics/hev-ev-multicell-balancing.html. [Accessed: 23-Jan-2017].
[304] Linear Technology, "LTC6802-1 - Multicell Battery Stack Monitor," *Multicell Battery Stack Monitor*, 2017. [Online]. Available: http://www.linear.com/product/LTC6802-1. [Accessed: 23-Jan-2017].
[305] NXP, "MC33771: 14-Channel Li-ion Battery Cell Controller IC," *NXP-Products*, 23-Jan-2017. [Online]. Available: http://www.nxp.com/products/power-management/battery-management/battery-cell-controllers/14-channel-li-ion-battery-cell-controller-ic:MC33771#community-discussions. [Accessed: 23-Jan-2017].
[306] "Functional and Safety Guide for Battery Management System (BMS) assessment and certification," Bureau Veritas, 2014.
[307] Industry ARC. Analytics. Research. Consulting., "Battery Management Systems Market: By Component (Power module, battery, Communication channel) Application (Energy Harvesting, Wireless Power Devices) Topology (Distributed, Modular, Centralized) End-User Industry (Automotive, Telecom)-Forecast(2015-2020)," *Industry ARC. Analytics. Research. Consulting.*, 15-Jan-2015. [Online]. Available: http://industryarc.com/Report/1270/battery-management-systems-market-analysis-report.html. [Accessed: 19-Jan-2017].
[308] Qy Research Groups, "Europe Power Battery Management System (BMS) Industry 2016 Market Research Report," *Qy Research Groups*, 23-Jun-2016. [Online]. Available: http://www.qyresearchgroups.com/report/europe-power-battery-management-system-bms-industry-2016-market-research-report. [Accessed: 19-Jan-2017].
[309] Davide Andrea, "Li-Ion BMS comparison, BMS selector," *Li-Ion BMS comparison, BMS selector*, 2008. [Online]. Available: http://liionbms.com/php/bms-selector.php. [Accessed: 12-Jan-2016].
[310] Wikipedia, the free encyclopedia, "LG Chem," *Wikipedia, the free encyclopedia*, Jan-2015. [Online]. Available: https://en.wikipedia.org/wiki/LG_Chem. [Accessed: 13-Feb-2017].
[311] Wikipedia, the free encyclopedia, "Samsung SDI," *Wikipedia, the free encyclopedia*, Jun-2016. [Online]. Available: https://de.wikipedia.org/wiki/Samsung_SDI. [Accessed: 13-Feb-2017].

[312] FindTheCompany, "General Motors Global Technology Operations Inc.," *FindTheCompany*, 13-Feb-2017. [Online]. Available: http://listings.findthecompany.com/l/13782112/Gm-Global-Technology-Operations-Inc-in-Detroit-MI. [Accessed: 13-Feb-2017].
[313] Bloomberg, "Company Overview of Ford Global Technologies, LLC," *Bloomberg*, 13-Feb-2017. [Online]. Available: http://www.bloomberg.com/research/stocks/private/snapshot.asp?privcapid=34040484. [Accessed: 13-Feb-2017].
[314] Wikipedia, the free encyclopedia, "Tesla, Inc.," *Wikipedia, the free encyclopedia*, 2017. [Online]. Available: https://en.wikipedia.org/wiki/Tesla,_Inc. [Accessed: 13-Feb-2017].
[315] Wikipedia, the free encyclopedia, "Nissan," *Wikipedia, the free encyclopedia*, 2017. [Online]. Available: https://en.wikipedia.org/wiki/Nissan. [Accessed: 13-Feb-2017].
[316] Wikipedia, the free encyclopedia, "Renault," *Wikipedia, the free encyclopedia*, 2017. [Online]. Available: https://en.wikipedia.org/wiki/Renault. [Accessed: 13-Feb-2017].
[317] Wikipedia, the free encyclopedia, "Mitsubishi Motors," *Wikipedia, the free encyclopedia*, 2016. [Online]. Available: https://en.wikipedia.org/wiki/Mitsubishi_Motors.
[318] Wikipedia, the free encyclopedia, "Toyota," *Wikipedia, the free encyclopedia*, 2017. [Online]. Available: https://en.wikipedia.org/wiki/Toyota. [Accessed: 13-Feb-2017].
[319] Wikipedia, the free encyclopedia, "Denso," *Wikipedia, the free encyclopedia*, 2016. [Online]. Available: https://en.wikipedia.org/wiki/Denso. [Accessed: 13-Feb-2017].
[320] Wikipedia, the free encyclopedia, "Delphi Automotive," *Wikipedia, the free encyclopedia*, 2017. [Online]. Available: https://en.wikipedia.org/wiki/Delphi_Automotive. [Accessed: 23-Jan-2017].
[321] Wikipedia, the free encyclopedia, "Preh," *Wikipedia, the free encyclopedia*, 2016. [Online]. Available: https://de.wikipedia.org/wiki/Preh. [Accessed: 23-Jan-2017].
[322] Sensor-Technik Wiedemann GmbH, "STW-Facts and figures," *STW-Facts and figures*, 23-Jan-2017. [Online]. Available: https://www.sensor-technik.de/en/company/facts-and-figures.html. [Accessed: 23-Jan-2017].
[323] REAP Systems, "REAP Systems Portal," *REAP Systems Portal*, 2016. [Online]. Available: http://www.reapsystems.co.uk/. [Accessed: 23-Jan-2017].
[324] Lian Innovative, "Lian Innovative-History," *Lian Innovative-History*, 2015. [Online]. Available: http://lianinno.com/history/. [Accessed: 23-Jan-2017].
[325] DATALOG, "Company Information for Tritium Pty Ltd.," *DATALOG-Company Overview*, 10-Jan-2016. [Online]. Available: http://www.datalog.co.uk/browse/detail.php/CompanyNumber/AU75095500280/CompanyName/TRITIUM+PTY+LTD. [Accessed: 23-Jan-2017].
[326] Elithion Inc., "Elithion-About Elithion," *Elithion-About Elithion*, 23-Jan-2017. [Online]. Available: http://elithion.com/about.php. [Accessed: 23-Jan-2017].
[327] LION E-MOBILITY AG, "LION E-Mobility AG - Company profile.," *LION E-Mobility AG - Company profile.*, 23-Jan-2017. [Online]. Available: http://www.lionemobility.de/en/company. [Accessed: 23-Jan-2017].
[328] Elite Power Solutions, "Elit Power Solutions Portal," *Elite Power Solutions*, 23-Jan-2017. [Online]. Available: http://www.elitepowersolutions.com/. [Accessed: 23-Jan-2017].
[329] Bloomberg, "Company Overview of Navitas Solutions, Inc.," *Bloomberg*, 23-Jan-2017. [Online]. Available: http://www.bloomberg.com/research/stocks/private/snapshot.asp?privcapId=183190214. [Accessed: 23-Jan-2017].
[330] ACTIA Group, "ACTIA Group-About us," *ACTIA Group-About us*, 2016. [Online]. Available: http://www.ime-actia.de/index.php/en/about-us. [Accessed: 23-Jan-2017].
[331] FindTheCompany, "Ewert Energy Systems," *FindTheCompany*, 23-Jan-2017. [Online]. Available: http://listings.findthecompany.com/l/33550648/Ewert-Energy-Systems-in-Carol-Stream-IL. [Accessed: 23-Jan-2017].
[332] Wikipedia, the free encyclopedia, "Valence Technology," *Wikipedia, the free encyclopedia*. [Online]. Available: https://en.wikipedia.org/wiki/Valence_Technology. [Accessed: 23-Jan-2017].

[333] EVPST Co. Ltd., "Electric Vehicle Power System Technology Co.,Ltd (EVPST). Company Profile.," *EVPST Co. Ltd. About us*, 2008. [Online]. Available: http://www.evpst.com/about.asp. [Accessed: 23-Jan-2017].
[334] Bloomberg, "Company Overview of Ashwoods Energy Limited," *Bloomberg*, 23-Jan-2017. [Online]. Available: http://www.bloomberg.com/research/stocks/private/snapshot.asp?privcapid=271438875. [Accessed: 23-Jan-2017].
[335] Stanislav Arendarik and Rožnov pod Radhoštem, "Active Cell Balancing in Battery Packs- Application Note." Freescale Semiconductor, Jan-2012.
[336] O2 Micro, "BATTERY MANAGEMENT," *O2 Micro - Products*, 2013. [Online]. Available: http://www.o2micro.com/products/battery-mgmnt.html. [Accessed: 07-Feb-2017].
[337] Maxim integrated, "MAX17823: 12-Channel, High-Voltage Sensor with Integrated Cell Balancing and Differential UART for Daisy-Chain Communication," *Maxim Integrated-Products*, 2017. [Online]. Available: https://www.maximintegrated.com/en/products/analog/sensors-and-sensor-interface/MAX17823.html?utm_source=Campaign%2520Microsite&utm_medium=Solution%2520Brief&utm_content=BMS%2520MAX17823&utm_campaign=Automotive%25202015. [Accessed: 07-Feb-2017].
[338] Texas Instruments, "EM1401EVM: Evaluation Module for Li-ion Automotive Monitoring and Protection System," *Texas instruments - Products*, 2016. [Online]. Available: http://www.ti.com/tool/em1401evm. [Accessed: 07-Feb-2017].
[339] Austriamicrosystems-AG, "AS8510 Analog Front-End Data acquisition IC for battery management, dual ADC," *Austriamicrosystems - Products*, 2017. [Online]. Available: http://ams.com/eng/Products/Battery-Management/Battery-Sensor-Interfaces/AS8510. [Accessed: 07-Feb-2017].
[340] Renesas Electronics, "Battery Management," *Renesas Electronics - Power Management*, 2017. [Online]. Available: https://www.renesas.com/en-us/products/power-management/battery-management.html. [Accessed: 07-Feb-2017].
[341] Atmel Corporation, "Atmel Li-Ion Battery Management Solution for Automotive and Industrial Applications." Atmel Corporation, 2011.
[342] Analog Devices, "AD7280A: Lithium Ion Battery Monitoring System. Data sheet." Analog Devices, 2016.

ANNEX A

Topology	PMU	Battery Management Module (BMM), System Interface Module (SIM), CAN Current Sensor (CCS)		
	MMU, CMU	Battery Management Module (BMM)		
Operation purpose	EV, PHEV, HEV			
Cell chemistry	Lithium iron phosphate			
Maximum pack size (serial cells/voltage)	1000 V			
Features	BMM	SOC/SOH/impedance estimation, balancing, voltage/temperature/current control		
	SIM	Communication gateway, contactor control		
	CCS	Current measurement, contactor contol		
Balancing current	900 mA			
Communication	CAN	BMM ↔ BMM, BMM ↔ SIM, BMM ↔ CCS, SIM ↔ Vehicle Controller		
Current measurement	Hall-effect (CCS)			
Main IC and characteristics	BMM	Voltage	Accuracy	10 mV
			Sampling Frequency	20 Hz
	CCS	Current	Resolution	400 mA
Additional features	Software to adjust BMS settings			
Location	Great Britain			
Quality of public information	Good			

Table A.1. Ashwoods Energy's BMS (Vayon) [52].

Topology	PMU	Battery Control Unit (BCU)
	MMU, CMU	Module Control Unit (MCU)
	PMU	HV switch box
Operation purpose	BEV, PHEV, HEV	
Maximum pack size (serial cells/voltage)	800 V	
Features	BCU	SOC/SOH estimation, relay control, pack-voltage measurement
	MCU	Voltage/temperature monitoring, balancing
	HV switch box	Current measurement, contactor control
Communication	CAN	BCU ↔ MCU, BCU ↔ exterior devices
	Variety of I/Os	
Current measurement	Internal (HV switch box)	
Main IC and characteristics	BCU	32 bit floating point CPU
	MCU	8 bit controller
Location	Austria	
Quality of public information	Regular - good	

Table A.2. AVL's BMS [53].

Topology	Centralized	
Operation purpose	Nissan Leaf	
Maximum pack size (serial cells/voltage)	96 cells, 360 V	
Balancing	Passive, 8,7 mA	
Communication	UART	
Main IC and characteristics	Master	Renesas PD70F3236BM
	Cell monitoring	NEC DS15110
Location	Japan	

Table A.3. Calsonic Kansei's Nissan Leaf-BMS [7].

Topology	PMU	Hybrid and EV Controller (HCU), Battery Management Controller (BMC)		
	MMU, CMU	Battery Management Controller (BMC),		
Operation purpose	BEV, PHEV, HEV			
Cell chemistry	Any Lithium-ion, NiMh			
Maximum pack size (serial cells/voltage)	450 V			
Features	BMC	SOC estimation, voltage/temperature/current monitoring, contactor control		
	HCU	Voltage/current protection, communication,		
Power supply	BMC	Power	<16 W (<1 A @ 16 V)	
Communication	HCU	CAN, LIN, Flexray (optional)		
Main IC and characteristics	BMC	Current	Error	1%
Location	Great Britain			
Quality of public information	Regular			

Table A.4. Delphi Technologies' Battery Management Controller [54].

Topology	Modular	
Operation purpose	Toyota Prius PlugIN	
Maximum pack size (serial cells/voltage)	56 cells/ 207 V	
Balancing	Active	
Communication	Serial Daisy-chain	
Main IC and characteristics	Master	Renesas PD79F0121A
	Cell monitoring	? 2P25 SF367
Location	Japan	

Table A.5. DENSO's Toyota Prius PlugIn-BMS [7].

Topology	PMU	EMS-CPU (CPU)		
	MMU, CMU	Sense Boards (SB)		
Operation purpose	BEV, PHEV, HEV, storage applications			
Cell chemistry	Any lithium-ion			
Maximum pack size (serial cells/voltage)	140 cells/ 500 V			
Features	CPU	SOC estimation, voltage/temperature/current control; pack-voltage/current monitoring, ground-fault detection		
	SB	Balancing, voltage/temperature monitoring		
Balancing current	500 mA			
Supply	Power		1,44 W (120 mA @ 12 V)	
	Possible voltages		8 – 20 V	
Communication	"Daisy chain"	CPU ↔ SB, SB ↔ SB		
	CAN/ Modbus (optional)	Data extraction		
Current measurement	Shunt sensor (internal)			
Main IC and characteristics	CPU	Current	Resolution	1 A
		Voltage	Error	< 1%
			Resolution	0,1 V
		Sampling frequency	3 Hz	
	SB	Voltage	Error	< 1%
			Resolution	0,1 V
		Temperature	Error	< 1%
Costs	CPU	$155		
	SB (4SB200-V7)	$122,50		
Location	USA			
Quality of public information	Good			

Table A.6. Elite Power Solutions' Energy Management System [55].

Topology	PMU	Lithium Pro Master (PMU)		
	MMU, CMU	(Multiple) Cell-Board (CB)		
Operation purpose	BEV, PHEV, HEV, stationary/marine/robot applications			
Cell chemistry	Any lithium-ion			
Maximum pack size (serial cells/voltage)	255 cells/ 840 V			
Features	PMU	SOC/SOH/impedance estimation, pack-voltage/temperature/current control, current monitoring, ground-fault detection, contactor and precharge control		
	CB	Balancing, voltage/temperature monitoring		
Balancing current	200 mA			
Power supply	Power		1,2 W (100 mA @ 12 V)	
Communication	CAN			
	RS232			
Current measurement	Hall-effect sensor (external)			
Main IC and characteristics	PMU	IC		Lithiumate EL02
	SB	IC		Lithiumate EL01
		Voltage	Accuracy	10 mV
		Temperature	Accuracy	4 °C
Additional features	Software to adjust BMS settings			
Location	USA			
Quality of public information	excellent			

Table A.7. Elithion's Lithiumate Pro [56].

Topology	PMU	Controlling Module (CM)		
	MMU, CMU	Testing Module (TM)		
Operation purpose	BEV			
Cell chemistry	Lithium iron phosphate			
Maximum pack size (serial cells/voltage)	64 cells/ 240 V			
Features	CM	SOC estimation, temperature/current monitoring, ground fault detection		
	TM	Voltage monitoring		
Communication	CAN	CM ↔ vehicular controller, CM ↔ monitoring system		
	RS485	CM ↔ Battery charger		
Main IC and characteristics	CM	Temperature	Error	< 1 °C
		Current	Error	0,50%
	TM	Voltage	Error	0,50%
Location	China			
Quality of public information	regular			

Table A.8. Electric Vehicle Power System Technology Co., Ltd's (EVPST) BMS-1 [57].

<table>
<tr><td>Topology</td><td colspan="2">Centralized</td></tr>
<tr><td>Operation purpose</td><td colspan="2">Ford Fusion</td></tr>
<tr><td>Maximum pack size (serial cells/voltage)</td><td colspan="2">76 cells/ 275 V</td></tr>
<tr><td>Balancing</td><td colspan="2">Passive, 17 mA</td></tr>
<tr><td>Communication</td><td colspan="2">Serial Daisy-chain</td></tr>
<tr><td rowspan="2">Main IC and characteristics</td><td>Master</td><td>Freescale MPC5534MVZ80</td></tr>
<tr><td>Cell monitoring</td><td>Analog Devices AD7280</td></tr>
</table>

Table A.9. Ford Fusion Hybrid's BMS [7].

<table>
<tr><td>Topology</td><td colspan="2">Centralized</td></tr>
<tr><td>Operation purpose</td><td colspan="2">Chevrolet Malibu Eco</td></tr>
<tr><td>Maximum pack size (serial cells/voltage)</td><td colspan="2">32 cells/ 115 V</td></tr>
<tr><td>Balancing</td><td colspan="2">Passive, 17 mA</td></tr>
<tr><td>Communication</td><td colspan="2">Serial Daisy-chain</td></tr>
<tr><td rowspan="2">Main IC and characteristics</td><td>Master</td><td>Renesas R5F714264FPV</td></tr>
<tr><td>Cell monitoring</td><td>Hitachi-HCC03-LLV1018</td></tr>
<tr><td>Location</td><td colspan="2">Japan</td></tr>
</table>

Table A.10. Hitachi's Chevrolet Malibu Eco-BMS [7].

<table>
<tr><td rowspan="2">Topology</td><td>PMU</td><td colspan="3">Master 4.5 (Master)</td></tr>
<tr><td>MMU, CMU</td><td colspan="3">Slave 6 (Slave)</td></tr>
<tr><td>Operation purpose</td><td colspan="4">BEV, PHEV, HEV, stationary applications</td></tr>
<tr><td>Cell chemistry</td><td colspan="4">Any lithium-ion</td></tr>
<tr><td rowspan="2">Features</td><td>Master</td><td colspan="3">Voltage/temperature/current control, current monitoring, contactor control</td></tr>
<tr><td>Slave</td><td colspan="3">Voltage/temperature monitoring, balancing</td></tr>
<tr><td rowspan="4">Power supply</td><td rowspan="2">Master</td><td>Power</td><td colspan="2">0,72 W (60 mA @ 12 V)</td></tr>
<tr><td>Possible voltages</td><td colspan="2">12 V – 24 V</td></tr>
<tr><td rowspan="2">Slave</td><td>Power</td><td colspan="2">0,05 W (4,36 mA @ 12 V)</td></tr>
<tr><td>Possible voltages</td><td colspan="2">10 V – 60 V</td></tr>
<tr><td rowspan="3">Communication</td><td>CAN</td><td colspan="3">Master ↔ Current Sensor, Master ↔ Slave, Master ↔ exterior devices</td></tr>
<tr><td>isoSPI</td><td colspan="3">Slave ↔ Slave</td></tr>
<tr><td>Master (additional)</td><td colspan="3">Ethernet, RS232</td></tr>
<tr><td>Current measurement</td><td colspan="4">Shunt sensor (external)</td></tr>
<tr><td rowspan="3">Main IC and characteristics</td><td>Master</td><td colspan="3">2 redundant processors</td></tr>
<tr><td rowspan="2">Slave</td><td rowspan="2">Voltage</td><td>Accuracy</td><td>5 mV</td></tr>
<tr><td>Resolution</td><td>12 bit</td></tr>
<tr><td>Additional features</td><td colspan="4">Software to adjust BMS settings</td></tr>
<tr><td>Location</td><td colspan="4">Germany</td></tr>
<tr><td>Quality of public information</td><td colspan="4">regular</td></tr>
</table>

Table A.11. I + ME ACTIA's BMS [58].

Topology	PMU, MMU, CMU		SX-Controller	
Operation purpose	Small EV, mobile, industrial applications			
Cell chemistry	Any lithium-ion			
Maximum pack size (serial cells/voltage)	S1		12 cells/ 55 V	
	S2		24 cells/ 110 V	
	S3		26 cells/ 165 V	
	S4		48 cells/ 200 V	
Features	SX-Controller		SOC/SOH/impedance estimation, balancing, voltage/temperature/ current monitoring and control, ground-fault protection (optional), contactor and pre-charge control	
Balancing current	300 mA			
Power supply	Power		1,44 W (60 mA @ 24 V)	
	Possible voltages		9 V – 32 V	
Communication	CAN, RS232		SX-Controller ↔ exterior devices	
Current measurement	Hall-effect sensor (external)			
Main IC and characteristics	Voltage	Error		0,12%
		Resolution		1,5 mV
	Temperature	Error		1,0%
		Resolution		0,1 °C
	Sampling frequency		20 Hz	
Additional features	Software to adjust BMS settings			
Certified standards	IEC 61508/ ISO 26262			
Location	Canada			
Quality of public information	Excellent			

Table A.12. JTT Electronics LTD's S-line [59].

Topology	PMU	X-BCU (BCU)		
	MMU, CMU	X-MCUP (MCUP)		
Operation purpose	BEV, PHEV, HEV, backup, industrial application			
Cell chemistry	Any lithium-ion			
Maximum pack size (serial cells/voltage)	240 cells/ 1000V			
Features	BCU	SOC/SOH/impedance estimation, voltage/temperature/current protection, pack-voltage/temperature/current monitoring, ground-fault detection, contactor and pre-charge control		
	MCUP	SOC/SOH/impedance estimation, voltage/temperature monitoring, balancing		
Balancing current	300 mA			
Power supply	BCU	Power	2,16 W (180 mA @ 12 V)	
		Possible voltages	9 V – 32 V	
	MCUP	Power	1,44 W (60 mA @ 24 V)	
		Possible voltages	24 V – 32 V	
Communication	CAN	BCU ↔ MCU, BCU ↔ exterior devices		
Current measurement	external			
Main IC and characteristics	BCU	Voltage	Error	0,10%
			Resolution	28 mV
		Temperature	Error	1,00%
			Resolution	0,1 °C
		Current	Error	2,50%
			Resolution	1,2 mV
	MCUP	Voltage	Error	0,12%
			Resolution	1,5 mV
			Sampling frequency	20 Hz
		Temperature	Error	1,00%
			Resolution	0,1 °C
Additional features	Software to adjust BMS settings			
Certified standards	IEC 61508/ ISO 26262			
Location	Canada			
Quality of public information	excellent			

Table A.13. JTT Electronics LTD's X-line [59].

Topology	Modular	
Operation purpose	Chevrolet Volt	
Maximum pack size (serial cells/voltage)	90 cells/ 360 V	
Balancing	Passive, 125 mA	
Communication	SPI Daisy-chain	
Main IC and characteristics	Master	Freescale S9S08DZ32
	Cell monitoring	STMicro L9763
Location	South Korea	

Table A.14. LG Chem's Chevrolet Volt-BMS [7].

Topology	PMU	Central Controller Unit (CCU), Power Control Unit (PCU)		
	MMU, CMU	Cell Boards (CB)		
Operation purpose	BEV, PHEV, HEV, stationary, marine, backup applications			
Cell chemistry	Any lithium-ion			
Maximum pack size (serial cells/voltage)	252 cells/ 900 V			
Features	CCU	SOC/SOH estimation, voltage/ temperature protection, contactor control		
	PCU	Pack-voltage/ current measurement, current protection, contactor and pre-charge control		
	CB	Balancing, voltage/temperature monitoring		
Balancing current	2000 mA (InnoCab/InnoLess)			
	500 mA (InnoTeg)			
Power supply				
Communication	CAN, RS485, BT, Wifi	CCU ↔ external devices		
	Wired or wireless (not further specified)	CB ↔ CCU		
Current measurement	Shunt sensor (PCU)			
Main IC and characteristics	CB	Temperature	Accuracy	1 °C
			Resolution	0,1 °C
Additional features	Wireless communication			
Location	China			
Quality of public information	Regular – good			

Table A.15. Lian Innovative's BMS [60].

Topology	PMU		BMCU	
	MMU, CMU		LMU	
Operation purpose	BEV, HEV, PHEV, industrial, marine, storage application			
Cell chemistry	Any lithium-ion			
Maximum pack size (serial cells/voltage)	S-BMS		256 cells/ 1000 V	
	S-BMS 9-16		16 cells/ 48 V	
Features	BMCU		SOC/SOH/impedance estimation, pack-voltage monitoring, voltage/temperature/current control, ground-fault detection, contactor and pre-charge control	
	LMU		Balancing, voltage/temperature monitoring	
Balancing current	840 mA			
Power supply	BMCU		Power	1,8 W (150 mA @ 12 V)
			Possible Voltages	9 V – 14 V
	LMU		Power	0,24 W (20 mA @ 12 V)
			Possible Voltages	9 V – 14 V
Communication	CAN		BMCU ↔ LMU, BMCU ↔ exterior devices	
	RS232		BMCU ↔ diagnostic interface	
Current measurement	Shunt sensor (external)			
Main IC and characteristics	BMCU	Pack-voltage	Accuracy	1 V
		Sampling frequency	5 Hz	
	LMU	voltage	Accuracy	2 mV
			Sampling frequency	1 Hz
		Temperature	Accuracy	1,5 °C
Additional features	Software to adjust BMS settings			
Certified standards	EN 61000-4-3			
Location	Denmark			
Quality of public information	Good – excellent			

Table A.16. Lithium Balance's S-BMS and S-BMS 9-16 [61].

Topology	PMU, MMU, CMU	Mk3-series	
Operation purpose	BEV, PHEV, HEV, stationary application		
Cell chemistry	Any lithium-ion		
Maximum pack size (serial cells/voltage)	Mk3-3x4smt	120 cells	
	Mk3x8	240 cells	
	Mk3x12	254 cells	
Features	Balancing, voltage/temperature monitoring, voltage control		
Balancing current	Mk3-3x4smt	2000 mA	
	Mk3x8	2200 mA	
	Mk3x12	50 mA	
Power supply	Mk3-3x4smt	Power	0,24 W (10 mA @ 24 V)
		Possible Voltages	7 V – 35 V
	Mk3x8	Power	0,144 W (3 mA @ 48 V)
		Possible Voltages	7 V – 35 V
	Mk3x12	Power	0,12 W (2 mA @ 60 V)
		Possible Voltages	7 V – 35 V
Communication	RS232, Regbus RJ		
Current measurement			
Main IC and characteristics	Sampling frequency	16 Hz	
Additional features	Software to adjust BMS settings		
	Proprietary communication line		
Costs	Mk3-3x4smt	$200	
	Mk3x8	$320	
	Mk3x12	$210	
Location	USA		
Quality of public information	Regular - good		

Table A.17. Manzanita Micro's Mk3x-line [62].

Topology	Modular	
Operation purpose	Mitsubishi iMiEV	
Maximum pack size (serial cells/voltage)	88 cells/ 330 V	
Balancing	Passive, 92 mA	
Communication	SPI Daisy-chain	
Main IC and characteristics	Master	NEC F3612M2
	Cell monitoring	Linear LTC6802G-2
Location	Japan	

Table A.18. Mitsubishi iMiEV's BMS [7].

Topology	PMU	Battery Managing Module (MM)		
	MMU, CMU	Battery Sensing Module (SM)		
Operation purpose	Automotive, mobility, storage, internet of things, sensor networks applications			
Cell chemistry	Any lithium-ion			
Maximum pack size (serial cells/voltage)	640 cells/ >1000 V			
Features	MM	No specifications given		
	SM	Balancing, voltage/temperature monitoring		
Balancing current	120 mA			
Power supply	SM	Current	400 µA (per cell)	
Communication	Wireless (AES-128, 2.4 GHz ISM Band)	MM ↔ SM		
Main IC and characteristics	SM	Voltage	Accuracy	2,5 mV
		Temperature	Accuracy	2 °C
Additional features	Software to adjust BMS settings			
	Wireless communication			
Certified standards	ISO 26262, CISPR25, ISO 11452, ISO 10605/16750			
Location	USA			
Quality of public information	Regular			

Table A.19. Navitas Solutions' Wireless BMS (WiBMS) [63].

Topology	PMU, MMU, CMU	Orion (Jr) BMS	
Operation purpose	Orion BMS	BEV, PHEV, HEV	
	Orion Jr BMS	Scooter, golf carts, solar, wind, backup apllications	
Cell chemistry	Any lithium-ion		
Maximum pack size (serial cells/voltage)	Orion BMS	180 cells/ 2000 V	
	Orion Jr BMS	16 cells/ 60 V	
Features	SOC/SOH/impedance estimation, balancing, voltage/temperature/current monitoring and control, ground-fault detection, contactor control		
Balancing current	Orion BMS	200 mA	
	Orion Jr BMS	150 mA	
Power supply	Orion BMS	Power	3 W (250 mA @ 12 V)
		Possible Voltages	8 V – 16 V
	Orion Jr BMS	Power	1,1 W
		Possible Voltages	11 V – 60 V
Communication	CAN	BMS ↔ BMS, BMS ↔ exterior devices	
	RS232	BMS ↔ programming and diagnostic interface	
Current measurement	Shunt or hall-effect sensor (external)		
Main IC and characteristics	Voltage	Accuracy	1,5 mV
		Resolution	0,25%
	Sampling frequency	33 Hz	
Additional features	Software to adjust BMS settings		
Certified standards	ISO 7637, EN 50498:2010, 2004/104/EC		
Costs	Orion	\$760 - \$1680	
	Orion Jr	\$425 - \$460	
Location	USA		
Quality of public information	Excellent		

Table A.20. Orion BMS - Extended Size and Orion BMS – Junior [64].

Topology	Modular	
Operation purpose	BMW i3	
Maximum pack size (serial cells/voltage)	96 cells/ 360 V	
Main IC and characteristics	Cell monitoring	Linear LTC6802G-2, LTC6801G, Freescale MC9S12P64
Location	Germany	

Table A.21. Preh GmbH's BMW i3-BMS [65].

Topology	PMU, MMU, CMU	REAP Li-Ion BMS
Operation purpose	BEV; PHEV, HEV, marine, stationary, military, racing applications	
Cell chemistry	Any lithium-ion	
Maximum pack size (serial cells/voltage)		
Features	SOC/SOH estimation, balancing, voltage/temperature/current monitoring and protection, contactor control	
Communication	CAN	BMS ↔ external devices
	RS232	BMS ↔ diagnostic and logging interfaces
	RS485/RS422 (optional)	BMS ↔ higher level vehicle controllers
Current measurement	Shunt or hall-effect sensor (external)	
Main IC and characteristics	Atmel AT90CAN128-16AU	
Location	Great Britain	
Quality of public information	Regular	

Table A.22. REAPsystems' BMS [66].

Topology	PMU	Battery Main Supervisor (BMS), Power Measurement Board (PMB)		
	MMU, CMU	Cell Sensor Circuit (CSC)		
Operation purpose	BEV, PHEV, HEV, agriculture, rail, transport, marine, stationary applications			
Cell chemistry	Any lithium-ion			
Maximum pack size (serial cells/voltage)	800 V			
Features	BMS	SOC/SOH estimation, temperature monitoring, voltage/temperature/current protection, ground-fault detection, contactor and pre-charge control		
	PMB	Pack-voltage/current monitoring		
	CSC	Balancing, voltage/temperature monitoring		
Balancing current	120 mA			
Power supply	BMS	Power	4,2 W (350 mA @ 12 V)	
		Possible Voltages	8 V – 32 V	
	PMB, CSC	Supply via BMS		
Communication	CAN	BMS ↔ PMB ↔ CSC, BMS ↔ exterior devices		
Current measurement	Shunt sensor (PMB)			
Main IC and characteristics	BMS	Temperature	Accuracy	2 K
	PMB	Voltage	Accuracy	0,1 V
		Current	Accuracy	0,1 A
	CSC	LTC6804		
		Voltage	Accuracy	2,5 mV
		Temperature	Accuracy	2 K
Additional features	Software to adjust BMS settings			
Location	Germany			
Quality of public information	excellent			

Table A.23. Sensor Technik Wiedemann's (STW) mBMS [67].

Topology	Modular	
Operation purpose	Tesla Model S	
Maximum pack size (serial cells/voltage)	96 cells/ 400 V	
Balancing	passive	
Main IC and characteristics	Cell monitoring	TI chip
Location	USA	

Table A.24. Tesla Motors' Model S-BMS [68].

Topology	PMU	Battery pack Management Unit (BMU)		
	MMU, CMU	Cell Management Unit (CMU)		
Operation purpose	BEV, PHEV, HEV			
Cell chemistry	Any lithium-ion			
Maximum pack size (serial cells/voltage)	256 cells/ 1000 V			
Features	BMU	SOC estimation, pack-voltage/temperature monitoring, voltage/temperature/current control, ground-fault detection, contactor and pre-charge control		
	CMU	Balancing, voltage/temperature monitoring		
Balancing current	250 mA			
Communication	CAN	CMU ↔ BMU, BMU ↔ exterior devices		
Current measurement	Shunt sensor (external)			
Main IC and characteristics	CMU	Voltage	Accuracy	1 mV
			Resolution/frequency circuit 1	24 bit/ 1 Hz
			Resolution/ frequency circuit 2	12 bit/ several kHZ
		Temperature	Accuracy	2 °C
Additional features	Software to adjust BMS settings			
Location	Australia			
Quality of public information	Good - excellent			

Table A.25. Tritium's IQ BMS [69].

Topology	PMU, MMU, CMU	U-BMS-series
Operation purpose	BEV, PHEV, HEV, marine, industrial, storage applications	
Cell chemistry	Any lithium-ion	
Maximum pack size (serial cells/voltage)	U-BMS-LV	150 V
	U-BMS-LVM	150 V/ 1000V (distributed)
	U-BMS-HV	450 V
	U-BMS-SHV	700 V
Features	SOC estimation, balancing, voltage/temperature/current monitoring and control, ground-fault detection, contactor and pre-charge control	
Communication	CAN	BMS ↔ exterior devices
Location	USA	
Quality of public information	Regular	

Table A.26. Valence U-BMS [70].

Topology	PMU, MMU, CMU	iBMS 8-18s
Operation purpose	Small EVs, scooters	
Cell chemistry	Any lithium-ion	
Maximum pack size (serial cells/voltage)	1000 V	
Features	SOC/SOH estimation, balancing, voltage/temperature/current monitoring and control, ground-fault detection	
Balancing current	150 mA	
Communication	CAN	iBMS ↔ exterior devices
Current measurement	Hall-effect sensor (external)	
Additional features	Software to adjust BMS settings	
Location	France	
Quality of public information	Regular	

Table A.27. Ventec SAS iBMS 8-18S [71].

Topology	PMU	Battery Monitoring Unit (BMU)
	MMU, CMU	Cell Monitoring Unit (CMU)
Operation purpose	BEV, PHEV, HEV	
Maximum pack size (serial cells/voltage)	96 cells	
Features	BMU	SOC/SOH estimation, voltage/temperature/current control
	CMU	Balancing, voltage/temperature/current measurement
Main IC and characteristics	BMU	FPGA chip
Additional features	SOC estimation with Kalman filter possible	
Location	USA	
Quality of public information	Good	

Table A.28. Altera's BMS [72], [73].

Topology	PMU	FoxBMS master (master)		
	MMU, CMU	FoxBMS slave (slave)		
Operation purpose	BEV, PHEV, HEV, aviation, space, marine, railway, industrial applications			
Cell chemistry	Any lithium-ion			
Maximum pack size (serial cells/voltage)	Arbitrary			
Features	Master	SOC/SOH estimation, voltage/temperature/current control, current monitoring, gorund-fault detection, contactor and pre-charge control		
	Slave	Balancing, voltage/temperature monitoring		
Balancing current				
Power supply	Power	1,8 W (150 mA @ 12 V)		
	Possible voltages	10 V – 26 V		
Communication	Master	CAN, RS232, USB, EEPROM, RS485, isoNOC		
	Slave	Iso-SPI, SPI		
Current measurement	CAN based current sensor (external)			
Main IC and characteristics	Master	IC		MCU 0, MCU 1
	Slave	IC		LTC 6820, STM32F429
		Voltage	Accuracy	1,2 mV
		Sampling frequency		> 3 kHz
Additional features	Software to adjust BMS settings, adaptable (also centralized topology possible)			
Location	Germany			
Quality of public information	Good - excellent			

Table A.29. Fraunhofer's foxBMS [74], [75].

Topology	PMU	Control Modular (LCM)		
	MMU, CMU	Measure Module (LMM)		
Operation purpose	BEV, PHEV, HEV, storage applications			
Cell chemistry	Any lithium-ion			
Maximum pack size (serial cells/voltage)	192 cells/ 800 V			
Features	LCM	SOC/SOH estimation, voltage/temperature/current control, temperature monitoring, ground-fault detection (optional), contactor and pre-charge control		
	LMM	Balancing, voltage/temperature monitoring		
Balancing current	50 mA			
Power supply	LCU	Power	1,8 W (150 mA @ 12 V)	
		Possible voltages	9 V – 18 V	
	LMM	Power	0,12 W (2 mA @ 60 V)	
		Possible voltages	10 V – 70 V	
Communication	IsoSPI	LMM ↔ LMM, LMM ↔ LCM		
	CAN, USB, UART	LCM ↔ exterior devices		
	Master (optional)	Bluetooth, SPI		
Current measurement	Shunt or hall-effect sensor (external)			
Main IC and characteristics	LCM	Microchip PIC32		
	LMM	LTC6804		
		Voltage	Accuracy	1,5 mV
		Temperature	Accuracy	1,5 °C
Additional features	Software to adjust BMS settings, open source software			
Location	Germany			
Quality of public information	good			

Table A.30. LION Smart's Li-BMS V4 [76].

Annex B

Table B.1. Relation of BMS, cells and battery packs manufacturers identified through the study.

Company Name	URL
123 Electric	http://www.123electric.eu/
A123 Systems	http://www.a123systems.com/lithium-battery.htm
AA Portable Power	http://www.aaportablepower.com/
AC Propulsion System	http://www.greencarcongress.com/2008/11/ac-propulsion-s.html
Adverc	http://www.adverc.co.uk/
AllCell Technologies	https://www.allcelltech.com/index.php/products/battery-packs
Amperex Technology	http://www.atlbattery.com/about/en/about-1.htm
Ashwoods Energy Limited (Vayon)	http://www.ashwoodsenergy.org
AVL	https://www.avl.com/battery-management-system-bms-development
BatteryMan	http://www.sdle.co.il/allsites/810/assets/batteryman_herzelia.pdf
Beckett Energy	http://beckettenergy.com/beckett-energy-systems-products/
Beijing Pride New Energy Battery Technology Co., Ltd.	http://www.pride-power.com/
Belktronix	http://www.belktronix.com/batmon.html
Bosh Battery Systems GmbH	http://www.bosch.de/de/de/our_company_1/business_sectors_and_divisions_1/battery_systems/battery_systems.html
Boston power	http://www.boston-power.com/products
Btech	http://www.btechinc.com/
C&C Power	http://www.ccpower.com/products/batt-safe-battery-monitoring/
CALB lithium battery	http://en.calb.cn/product/show/?id-633
Calsonic Kansei (Nissan)	https://www.calsonickansei.co.jp/english/products/electronic/lbc.html
Chargery	http://www.chargery.com/
China Aviation Lithium Battery Co., Ltd.	http://en.calb.cn/product/show/?id-626
Clayton Power	http://www.claytonpower.com/products/bms/
Clean Power Auto LLC	http://cleanpowerauto.com/product-support/
Contemporary Amperex Technology Co. CATL	http://www.catlbattery.com/index.php/solution-typeid-16.html#
Continental	http://www.continental-corporation.com/www/pressportal_com_en/themes/press_releases/3_automotive_group/powertrain/press_releases/pr_2008_09_24_liion_batteries_en.html
CorvusEnergy	https://corvusenergy.com/technology-specifications/
Daimler (Accumotive)	http://www.accumotive.de/de/produkte.html
Delphi Automotive PLC	http://delphi.com/manufacturers/auto/hevevproducts/controllers/bmc/
Denso	http://denso-europe.com/wp-content/uploads/2011/08/batteryECU.jpg
DOW KOKAM (Xalt Energy)	http://kokam.com/cell/
EaglePicher Technologies, LLC	http://www.eaglepicher.com/r-n-d/new-product-development/battery-management-systems
Elektromotus	https://www.elektromotus.lt/product-category/emus-bms/
Elite Power Solutions	http://elitepowersolutions.com/packages.html

Elithion	http://elithion.com/products.php#Off-the-shelf_BMSs
EnerDel	http://www.enerdel.com/packs/
Epower Electronics	http://www.hzepower.com/Home/Index#1
EV power	http://www.ev-power.com.au/-Thundersky-Battery-Balancing-System-.html
Evaira	http://emsys-design.com/index.php
EVLithium	http://webshop.evlithium.net/index.php?cPath=26_25
EVPST	http://www.evpst.com/Product.asp?bid=29&BigClassName=EV%20BMS
Fedco Batteries	http://www.fedcobatteries.com/
Flux Power Inc.	http://www.fluxpwr.com/products/technology/
Fraunhofer IIS	https://www.foxbms.org/typo3/index.php?id=foxbms
G4 Synergetics	http://www.g4synergetics.com/index.php/products-main
Gold Up New Energy	
GuanTuo Power	http://guantuopower.en.made-in-china.com/product/eqJQnMxgIUpw/China-Lithium-Battery-BMS-GTBMS005A-MC16-.html
Guoxuan High-tech Power Energy	http://www.bloomberg.com/research/stocks/private/snapshot.asp?privcapId=312416846
Hangzhou Jieneng Power Co., Ltd.	
High Tech Systems	http://hightechsystems.weebly.com/bms.html
Hitachi Automotive Systems	http://www.hitachi.com/New/cnews/month/2016/04/160420.pdf
Hyundai Kefico	https://www.hyundai-kefico.com/en/business/evms_electric.do
I + ME ACTIA	http://www.ime-actia.de/index.php/en/solutions-for-vehicle-manufacturers/solutions-for-cars/battery-management-systems
Jiangsu Highstar Battery Manufacturing	http://www.highstarbattery.com/gsjj/
Johnson Matthey Battery Systems	http://www.jmbatterysystems.com/technology/battery-management-systems-(bms)
Jon Elis	http://www.diyelectriccar.com/forums/showthread.php/new-bms-offerings-jon-elis-low-84280.html
JTT Electronics LTD.	http://www.jttelectronics.com/products/cat/battery-management-systems
Just Power	http://eentsv2.ee.nsysu.edu.tw/eehome/seminar/docbank/Seminar00028.pdf
K2 Energy	http://www.k2battery.com/systems.html
Kopf	http://www.kopfweb.de/index.php/en/Entwicklung/component/content/article/8-entwicklung/50-development-batterie-management-systeme-bms-for-hybrid-and-electrical-vehicles
L&T Technology Services	http://www.lnttechservices.com/solutions/power-electronics/battery-management/
Leoyun New Energy	http://www.qqdcw.com/product/mbr111213024130531517/pro111213024354968585.xhtml
LG Chem/ LG CPI (LG)	http://www.lgchem.com/global/vehicle-battery/car-batteries-Different/product-detail-PDEB0002
Lian	http://lianinno.com/battery-management-systems/
LIGOO New Energy Technology	http://www.ligoo.cn/en/products.asp?class_id=20021001
LiPoTech	http://www.lipotech.net/industria/index.php?option=com_content&view=article&id=1&Itemid=94

Lithium Balance Corporation	http://www.lithiumbalance.com/en/component/product/categories/19
Manzanita Micro	http://www.manzanitamicro.com/products?page=shop.browse&category_id=36
Merlin Equipment Ltd.	http://www.merlinequipment.com/markets/group.asp?groupid=59
Microvast Inc.	http://www.microvast.com/index.php/solution/solution_cell
Midtronics	http://www.midtronics.com/shop/products-1/integrated-solutions/midtronics-ing-100-battery-monitor
Narada Power Source	http://en.naradapower.com/index.php/technologies?ctype=57
Navitas solutions	http://www.navitasone.com/
Navitas System, LLC	http://www.navitassys.com/products-systems/battery-management-systems-bms/
NEC	https://www.neces.com/products-services/battery-systems/battery-components-and-accessories/
Ningbo Bate Technology Co., Ltd.	https://www.bloomberg.com/profiles/companies/NBBTTZ:CH-ningbo-bate-technology-co-ltd
Ningbo Longway Electrical Co., Ltd.	http://www.yangming.com.cn/english/ProductsView.asp?ID=18&SortID=10
Nuvation Engineering	http://www.nuvation.com/battery-management-system
Octillon Power Systems	http://www.octillion.us/energy-storage-products
Orion BMS	http://www.orionbms.com/resources/
Panasonic	http://www.semicon.panasonic.co.jp/en/applications/automotive/ev_hev/bms/#t1
Peter Perkins	http://batteryvehiclesociety.org.uk/forums/viewtopic.php?t=1245
PowerShield	https://www.powershield.com/
Preh	http://www.preh.com/produkte/e-mobility/
REAP Systems	http://cgi.ddoerffel.force9.co.uk/_products/products_BMS.html
REC BMS	http://www.rec-bms.com/
Redarc Electronics	https://www.redarc.com.au/battery-chargers/battery-management-systems
Rimac Automobili	http://storage.rimac-automobili.com/b2b-materials/docs/battery-management-system-and-battery-packs/RA_BMS_Detailed.pdf
Rotronics	http://www.rotronicsbms.com/our-products/
Rozwiazania dla EV	http://rs232.elektroda.eu/?page_id=385
Saftbatteries	http://www.saftbatteries.de/market-solutions/mobility
Samsung SDI	http://www.samsungsdi.com/automotive-battery/index.html
Sensor Technik Wiedemann (STW)	https://www.sensor-technik.de/en/products.html?view=product&stwpid=14
Setec Pty Ltd.	http://www.setec.com.au/portfolio/genius-battery-management-system/
Shenzhen Antega Technology Co., Ltd.	http://ccne.mofcom.gov.cn/1282430
Shenzhen Battsiter Tech Co., Ltd.	
Shenzhen Klclear Technology	http://www.klclear.com/productslist.asp?sortid=49&l=en
Shenzhen OptimumNano Energy	http://www.optimumnanoenergy.com/index.php?c=product&cid=54
SINOEV Technologies	http://www.sinoev.com/traction-battery-pack/
SK Innovation	https://cleantechnica.com/2016/09/22/sk-innovation-raises-battery-production-25/

Sony	http://www.sony.net/SonyInfo/News/Press/201104/11-053E/
Sunwoda Electronic	
TESVOLT	http://www.tesvolt.com/bidirectional-battery-management-system.html
Torqeedo	http://www.torqeedo.com/en/products/batteries/power-26-104/2103-00.html
Toshiba Corporation	https://www.toshiba.co.jp/about/press/2011_11/pr1701.htm
Tritium	http://tritium.com.au/products/iq-battery-management-system/
TWS (Technology with Spirit)	http://www.tws.com/web/index.php/technology/bms/
Valence Technology	https://www.valence.com/products/battery-management-systems/
Vecture Inc.	http://www.eberspaecher-vecture.com/bms/technology/designing-the-optimal-bms.html
Ventec Inc.	http://ventec-ibms.com/en/embedded-bms-solutions/ventec-ibms-8-18s-packs-in-series/
Voltabox	http://www.voltabox.com/products/modular-system/battery-management-system-bms/
Winston Battery	http://en.winston-battery.com/
Wuhu Tianyuan Automobile Electric Co., Ltd.	
Zanthic	http://www.zanthic.com/project31.htm