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

D6.7 – Battery Management System Standard

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Author(s)	Bharanitharan Jayaraman (LION Smart) Prashanth Vemireddy (LION Smart)
Reviewer(s)	Khiem Trad (VITO) Niles Fleischer (ALGOLiON) Jacobs Geert (VITO) Mulder Grietus (VITO) Sebastian Ludwig (TUM) Michael Geppert (LION Smart) Everhard Ros (LION Smart) Mario Beier (DIN)
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SCOPE

This document is intended to be applied to functional BMS development. It presents the standardization potential of the knowledge attained and results achieved in BMS research and development of the EVERLASTING project. It is focused on the functionality and generic design architecture of hardware and software aspects during the development of a generic BMS. This document should be seen as a proposal of a common, pre-normative technical standard for BMS architectures and functionalities, as a preparation for national and international standardization efforts.

TABLE OF CONTENTS

List of Abbreviations and Acronyms

ACRONYM	DEFINITION
WP	Work Package
WPL	Work Package Leader
DOW	Description of Work
BMS	Battery Management System
PCB	Printed Circuit Board
OCV	Open Circuit Voltage
SoC	State of Charge
SoH	State of Health
SoF	State of Function
SoP	State of Power
SoE	State of Energy
RT	Room Temperature
Top_{min}	Minimum Operating Temperature
Top_{max}	Maximum Operating Temperature
U_{min}	Minimum Voltage
U_{max}	Maximum Voltage
$U_{nominal}$	Nominal Voltage
PC	Personal Computer
EV	Electric Vehicle
SPI	Serial Peripheral Interface
I2C	Inter-Integrated Circuit
HV	High voltage
VCU	Vehicle Control Unit
OBD	On-board diagnostics
RUL	Remaining useful life
CAN	Controller Area Network
EMU	Energy Management Unit
ASIL	Automotive Safety Integrity Level
HMI	Human Machine Interface
RMS	Root Mean Square

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Battery management systems (BMS) can be defined as a safety control system required for managing of individual cells of the battery pack and an entire battery pack. This document is an endeavor to define and specify standard BMS functionalities and tests to verify/validate them. An analysis of existing standards to support development and verification of a BMS are listed in the next chapter. To analyse the deficiency of the listed documents to fulfil the requirements of a generic BMS, a gap analysis is being formulated. In the scope of the EVERLASTING project, the findings and the gap analysis are put together and executed. The results are detailed in chapter 3.

This document is an effort to standardize elements of BMS and its development. The prominent goals of a BMS are:

1. Protection of individual cells and battery systems from damage.
2. Increasing safety and reliability of battery systems.
3. Improving battery energy usage efficiency.
4. Prolong battery lifetime.

During the development of a BMS, there are various aspects to be considered to assure the safe operation and best possible utilization of the battery system. The analysis of existing standards for battery packs in different applications, and the functional safety standards like ISO 61508 and ISO 26262 for the development of hardware and software parts of electrical and electronic systems and gap analysis, promoted a proposal for BMS functional aspects and their validation through tests.

A specific application and its operational mode would specify further failures and their modes. This augmentation of challenges could be further worked up with tailored functional safety methods. The most important task of the BMS is to fulfil safety functions in such a way that the cells in a battery pack are operated within their specified limits in terms of voltage, temperature and current.

With application requirements getting more and more complex, different kind of risks and failures may occur beginning from the design and development phases, through testing, implementation and finally decommissioning and disposal phase. Hence for proper handling of such complex systems throughout their service lifetime, relevant standards should be developed for each stages of the product.

The results of the BMS standardization workshop conducted by LION Smart GmbH on 09.05.2019 were also taken into consideration while writing this document.

1 Background on Standardization

This section defines a standard, the standardization process and why standards are needed. Various standardization organisations which define standards on European and International level shall be mentioned along with standardization bodies which are specific to the automotive industry.

1.1 What is a Standard?

According to the International Organization for Standardization (ISO), "a standard is a document that provides requirements, specifications, guidelines or characteristics that can be used consistently to ensure that materials, products, processes and services are fit for their purpose. International Standards bring technological, economic and societal benefits. They help to harmonize technical specifications of products and services making industry more efficient and breaking down barriers to international trade" [1].

1.2 Relevant standardization bodies

1.2.1 European Standards Organizations (ESOs)

European Standards Organizations (ESOs) are standardization bodies responsible for developing European Standards. CEN, CENELEC and ETSI are recognised as 'European Standards Organisations' by the European Union.

1.2.1.1 CEN (European Committee for Standardization)

CEN, the European Committee for Standardization, which has been recognized by both European Union and European Free Trade Association (EFTA), is an association that coordinates all the National Standardization Bodies functioning in the European Union (EU) member states in order to develop standards at EU level.

CEN is a platform for the development of products, materials, services and process related European Standards and CEN supports standardization activities across various fields including: defense and security, air and space, chemicals, construction, consumer products, energy, the environment, food and feed, health and safety, healthcare, machinery, materials, services, transport etc.

In order to prepare state-of-the-art standards, CEN relies on the knowledge of around 50.000 experts, who work in various projects conducted through 33 Member state National Standards Bodies and 17 additional Affiliated bodies. Representation and contributions from stakeholders, consumers, workers, environmental enthusiasts are also included in the standard formulation processes.

The CEN Technical Board is also responsible for evaluating and addressing requests for standardization on new subjects in-addition to managing ongoing activities. The provisions for exchange of information between International Organization for Standardization (ISO) and CEN, mutual representation at meetings, and parallel approval of standards is provided by the Vienna Agreement. [1]

1.2.1.2 CENELEC (European Committee for Electro-technical Standardization)

CENELEC is the European Committee for Electro technical Standardization and is responsible for standardization in the electro-technical engineering field. CENELEC prepares voluntary standards, which help facilitate trade between countries, create new markets, cut compliance costs and support the development of a Single European Market.

CENELEC creates market access at the European level but also at the international level, adopting international standards wherever possible, through its close collaboration with the International Electro technical Commission (IEC), under the Dresden Agreement.

In an ever more global economy, CENELEC fosters innovation and competitiveness, making technology available industry-wide through the production of voluntary standards.
Through the work of its members together with its experts, the industry federations and consumers, European Standards are created in order to encourage technological development, to ensure interoperability and to guarantee the safety and health of consumers and provide environmental protection.

Designated as a European Standards Organization by the European Commission, CENELEC is a non-profit technical organization set up under Belgian law. It was created in 1973 as a result of the merger of two previous European organizations: CENELCOM and CENEL [1] .

1.2.1.3 ETSI (European Telecommunications Standards Institute)

ETSI produces globally-applicable standards for Information and Communications Technologies (ICT), including fixed, mobile, radio, converged, aeronautical, broadcast and internet technologies and is officially recognized by the European Union as a European Standards Organization.

ETSI is an independent, not-for-profit association whose 740 member companies and organizations, drawn from 62 countries across 5 continents worldwide, determine the ETSI work programme and participate directly in its work [1].

1.2.2 International Standards Organizations

1.2.2.1 ISO (International Organization of Standardization)

ISO, the International Organization for Standardization, is an independent, non-governmental organization, the members of which are the standards organizations of the 164 member countries. It is the world's largest developer of voluntary international standards and facilitates world trade by providing common standards between nations. Nearly twenty thousand standards have been set, covering everything from manufactured products and technology to food safety, agriculture and healthcare.

The use of standards aids in the creation of products and services that are safe, reliable and of high quality. The standards help businesses increase productivity while minimizing errors and waste. By enabling products from different markets to be directly compared, they facilitate companies in entering new markets and assist in the development of global trade on a fair basis. The standards also serve to safeguard consumers and the end-users of products and services, ensuring that certified products conform to the minimum standards set internationally [1].

1.2.2.2 IEC (International Electro technical Commission)

Founded in 1906, the IEC (International Electro technical Commission) is the world's leading organization for the preparation and publication of international standards for all electrical, electronic and related technologies. These are known collectively as "electro-technology".

IEC provides a platform to companies, industries and governments for meeting, discussing and developing the international standards they require.

All IEC international standards are fully consensus-based and represent the needs of key stakeholders of every nation participating in IEC work. Every member country, no matter how large or small, has one vote and a say in what goes into an IEC international standard [1].

1.2.2.3 ITU (International Telecommunication Union) – ITU-T

The International Telecommunication Union (ITU) is the United Nations specialized agency specialized in developing international standards in the field of telecommunications, information and communication technologies (ICTs).

The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organ of ITU. ITU-T is responsible for studying technical, operating and tariff questions and issuing recommendations on them with a view to standardizing telecommunications on a worldwide basis [1].

1.2.3 Other Standards Development Organizations

1.2.3.1 AUTOSAR

The AUTOSAR is an alliance of OEM manufacturers and Tier 1 automotive suppliers for development of a de-facto open industry standard for automotive E/E architecture which can serve as a basic infrastructure for the management of functions within existing standard software modules and also for implementation in future applications.

AUTOSARs goals are:
- Standardization of basic software functionality of automotive ECUs
- Scalability to different vehicle and platform variants
- Transferability of software
- Support of different functional domains
- Definition of an open architecture
- Collaboration between various partners
- Development of highly dependable systems
- Support of applicable automotive international standards and state-of-the-art technologies

The AUTOSAR scope includes all vehicle domains. This standard is intended to minimize the current barriers between functional domain and map functions, functional networks to different control nodes in the system, almost independently from the associated hardware [1].

2 Mapping of relevant standards and standardization gap analysis for BMS

2.1 Overview of relevant standards for BMS

This section contains a list of standards that are applicable to various battery systems applications.

2.1.1 Standards for battery systems in general

IEC 61508: This standard defines the design and safety requirements that must be considered while designing a programmable electric and electronic system for safe operation [2].

IEC 60068-2: This standard defines a set of functional and safety tests to study the influence of operating environmental conditions like humidity, temperature, vibration, shock etc., on the behavior of electronic equipment [3].

CENELEC CLC/TC 21X: This technical committee defined a set of tests for validating the performance and safety requirements of batteries used across applications [4].

EN 62485: This standard defines a set of tests to validate safe operation of battery systems, safety precautions and facilities to be present in the installations of the battery system application too [5].

UL 1974: This standard defines a set of potential 2nd life applications for EV batteries and lists the requirements that should be satisfied by an EV battery in order to efficiently serve the intended 2nd life application. The tests required to validate the application specific battery systems requirements are also mentioned [6].

2.1.2 Standards for application specific battery systems

All the standards and manuals evaluated in this section are formulated mainly focused on battery systems.

2.1.2.1 Standards related to electric vehicles

IEC 62660: This standard defines a set of requirements for cells in an electric vehicle battery for performance, safety, remaining useful life estimation, and a set of tests to validate these functionalities. [7]

ISO 26262: ISO 26262 is an automotive standard. It is an adaptation of IEC 61508 specific to the application sector of series production passenger cars with a maximum gross vehicle mass up to 3500 kg, which can be applied to all the activities during the safety lifecycle of safety-related systems comprising of electrical, electronic and software components. [8]

IEC JWG 69 Li TC69/21/5C21A: This joint working group defined a set of general requirements for the lithium ion battery systems used in automotive applications. Set of tests are specified for testing safety, performance functionalities, and battery pack's eligibility for serving a 2nd life applications. [9]

ISO 12405: This standard defines a set of reliability, abuse and performance tests for validation of lithium-ion traction batteries for use in electric vehicles. Both high energy and high-power applications are addressed in this standard. [10]

ISO 6469-2: This standard defines a set of safety requirements of components and subsystems present in electrically propelled road vehicles. This includes requirements and validation of safety and performance functionalities. [11]

ISO 6469-3: This standard defines a set of safety requirements and test for validating the passenger safety requirements of electrically propelled road vehicles. It focuses on prevention of electric shock due to internal short circuit or crash. [12]

ISO 16898: This standard deals with dimensions and designation of secondary lithium-ion cells for Electric vehicles. It gives guidance on tailoring a battery system design for a specific application and adopting its dimensions in order to fit into the designated application. [13]

SAE J1766: This standard defines a set of crash integrity requirements of electric vehicles, fuel cell and hybrid electric vehicles. In the scope of passenger vehicles, the tests for assuring the safety aspects like prevention of electric shock, exposure to high voltage, exposure to electrolyte spillage etc. are treated. [14]

SAE J2464: This standard defines a set of the safety and abuse tests for validation of rechargeable energy storage systems used in electric and hybrid electric vehicles. [15]

SAE J2380: This standard defines a set of the requirements, test profiles and test procedures for performing vibration on electric vehicle batteries. The scope of the standard for battery packs is mechanical vibration tests. [16]

SAE J2929: This standard defines a set of safety standard functionalities that must be satisfied by lithium-ion battery systems used in electric and hybrid vehicle propulsion. [17]

EN 50604-1: This standard defines a set of test procedures for validating the safety and performance functionalities of battery systems for implementation in light electric vehicle batteries. [18]

EN 61982: This standard defines a set of performance and endurance tests for validation of implementation of secondary batteries (except lithium) for the propulsion of electric road vehicles. [19]

IEC 62619: This standard defines a set of tests to be conducted for validating the safe operation of industrial battery systems implemented in both stationary and motive applications (forklifts, line mover etc.). It contains the requirement that the BMS should be designed according to the Functional Safety approach. [20]

USABC test procedure manual: This manual defines a set of safety, abuse and performance tests required for validating the battery systems for electric vehicle batteries. [21]

UL 2580: This standard defines a set of abuse tests to ensure safe operation of the energy storage assembly (battery pack/battery pack and ultra-capacitor etc.) in an electric vehicle. Performance and reliability tests of energy storage systems are not in the scope of this standard. This standard is applicable to medium and heavy electric vehicles like, passenger cars, trucks etc. and is not applicable to light electric vehicles like, e-bikes, e-wheelchairs, e-scooters etc. [22]

UL 2271: This standard is similar to UL 2580, defining a set of abuse tests to ensure safe operation of the energy storage assemblies (battery pack/battery pack and ultra-capacitor etc.). It is applicable to only light electric vehicles applications like, e-bikes, e-wheelchairs, e-scooters etc., which are not intended to be driven on highways. [23]
SAE J2288: This standard defines life cycle test methods to predict EV battery cycle life. This is done by characterizing the expected degradation in its electrical performance as a function of life, and by

identifying the relevant failure mechanisms under nominal operating conditions. Ageing due to operating at lower or higher temperatures in comparison to target application are not in the scope of the tests Modules are continuously cycled (20% DOD + complete charging) until their capacity and power capabilities fall below 80% of their beginning of life values. [24]

SAE J1798: This standard defines a set of performance tests to estimate parameters of an electric vehicle battery pack like, deliverable capacity at various discharge current, discharge power, operating temperatures, dynamic load profiles and etc. These tests are for estimating factors like dependence of self-discharge on battery pack rest time and its ambient temperature. And, also dependence of charge acceptance and peak power performance capabilities on ambient temperature. [25]

2.1.2.2 Standards related to stationary applications

IEC 61427 series: This standard defines a set of tests required for validating the performance and safety requirements of a battery system employed in on-grid/off-grid applications. Its primary focus is on battery performance and safety. Additionally, BMS related aspects like battery-grid communication protocol, adoption of an end-of-life EV-battery system are defined. [26]

2.1.2.3 Standards related to portable applications

IEC 62133 series: This standard defines a set of safety requirements and tests for the safe operation of rechargeable cells and batteries across chemistries for portable applications in part I, and performance in part II. This includes cells of different geometry and format, except for button cells. [13]

2.1.2.4 Standards related to electrical and electronic equipment

ISO 20653 This standard defines a set of tests to validate the protection and safety requirements to be satisfied by electrical equipment used in road vehicles in case of crash, water intrusion or unauthorised external access [27].

CENELEC CLC/TC 69X: The technical committee defined a set of general requirements for electrical systems used in EVs and defines the performance and safety functionalities validation tests of those system [28].

LV148 automotive standard: This standard defines a set of general requirements for electrical systems used in automotive applications operating at 48 V voltage level and states the tests need to be performed to validate the performance and safety functionalities of the system. [29]

LV124 automotive standard: This standard defines a set of general requirements for electrical systems used in automotive applications operating at 12 V voltage level and states the tests need to be performed to validate the performance and safety functionalities of the system. [30]

2.1.2.5 Overview

From a BMS point of view, the topics to be covered by the developed standard shall be grouped into major categories. These categories are listed below:

1. Functionality
2. Safety
3. Testing
4. Re-usability/second life and
5. Virtualization

The standards listed in the section above were analysed and the breadth of their coverage of the above listed categories is summarized in Table 1.

Standard	Application	Functionality	Safety	Testing	Performance	Reusability/second-life	Virtualization
IEC 62660	Li-ion cells for propulsion of electric vehicles	×	×	×	×	×	
IEC 61508	Programmable electric and electronic systems	×	×				
IEC 61982	Electric vehicles battery systems		×	×	×		
IEC 62984	High temperature secondary batteries		×	×	×		
IEC 61427	On-grid/off-grid energy storage application		×	×	×	×	
IEC 62619	Safety requirements for large format secondary lithium cells and batteries for stationary and motive applications	×	×	×			
IEC 62196-1	Conductive charging hardware requirements	×		×	×		
IEC 61851	Conductive charging hardware requirements up to 1000 V DC	×		×	×		

IEC 62196-2	Slow (private) and fast (public) charging standards	×	×	×	×		
IEC JWG 69 Li TC69/21/5C2 1A	Lithium for automotive applications	×		×	×	×	
IEC 60068-2	Environmental testing of electronic equipment	×	×	×			
IEC 62133	Safety requirements of portable sealed secondary cells and batteries		×	×			
AEC - Q100	IC failure mechanism-based quality check standards	×	×	×			
ISO 26262	Road vehicles – Functional safety	×	×	×			
ISO 12405	Electrically propelled road vehicles- Test specification for lithium-ion traction		×	×	×		
ISO 6469-2	Safety requirements of Electrically propelled road vehicles.		×	×			
ISO 6469-3	Passenger safety		×	×			

	requirements of Electrically propelled road vehicles.						
ISO16898	Dimensions and designation of secondary lithium-ion cells for Electric vehicles.			×	×		
ISO11898	Communication protocol standards in automation	×		×	×		
ISO 20653	Road vehicles electrical equipment protection against foreign objects, water and access		×	×			
ISO 17826	Cloud Data Management Interface	×		×			
SAE J1766	Electric, Fuel Cell and Hybrid Electric Vehicle Crash Integrity Testing		x	x			
SAE-J2284	High-Speed CAN (HSC) for Vehicle Applications	x		x	x		
SAE J2464	Electric and Hybrid Electric Vehicle		x	x			

	Rechargeable Energy Storage System (RESS) Safety and Abuse Testing						
SAE J2380	Vibration Testing of Electric Vehicle Batteries			x			
SAE J2929	Electric and Hybrid Vehicle Propulsion Battery System Safety Standard - Lithium-based Rechargeable Cells	x	x	x			
SAE J1798	Recommended Practice for Performance Rating of Electric Vehicle Battery Modules			x	x		
SAE J2288	Life Cycle Testing of Electric Vehicle Battery Modules			x	x	x	
SAE JA 6268	Design and Run-Time Information Exchange for Health-Ready Components	x	x		x		x
IEEE P2413	Architecture framework	x			x		x

	description for the Internet of Things (IoT) across multiple domains (transportation, smart grid, etc.)						
CENELEC CLC/TC 21X	Secondary cells and batteries requirements across applications		×	×	×		
CENELEC CLC/TC 69X	Electrical systems for electric road vehicles		×	×	×		
EN 50604-1	Test standard for Light Electric Vehicle batteries	×	×	×			
EN 62485	Safety requirements for secondary batteries and battery installations	×	×	×	×	×	
EN 61982	Secondary batteries (except lithium) for the propulsion of electric road vehicles - performance and endurance tests		×	×	×		

LVS 148	Automotive norm for validation of 48 V electrical systems		×	×	×		
LVS 124	Automotive norm for validation of 24 V electrical systems		×	×	×		
VW 80000 standard	Automotive norm for validation of 12 V electrical systems		×	×	×		
IEC 27018	Cloud computing standard	×			×		×
ITU-T X.1631	Cloud storage cyber security standards	×	×				×
UL 1974	Standard for Evaluation for Repurposing Batteries			×	×	×	
UL 2271	Standard for Batteries for Use in Light Electric Vehicle (LEV) Applications	×	×	×			
UL 2580	Batteries for Use in Electric Vehicles	×	×	×			

USABC test procedure manual	Electric vehicle battery test manual	×	×	×	×	×	
OBD-II	On-Board Diagnostics standard	×	×			×	×

Table 1: Standards relevant to an EV Battery management system

2.2 STANDARDIZATION GAP ANALYSIS FOR BMS

Although there are a considerable number of standards for battery served applications in existence, adopting and interpolating them with a focus on BMS seems challenging.

Hence, the standards listed in the section above were analysed for identifying the inadequacies and issues that should be bridged for a complete standardization effort of various aspects of BMS development.

Focus	**Identified gap**
Cell monitoring	Voltage, current and temperature monitoring of cells in the battery pack.
Communication protocol	Internal and external communication protocols (type, transmission rate etc.) must be defined.
Data format	Data transmission and storage formats must be defined for both on-board and server-based processing and storage purposes.
State estimation	Unified definition of state estimation parameters like SoC, SoH, SoP, SoE and SoF.
Test procedures	Real world load cycle based aging cycle definition for accurate life testing.
	Standard full charge and standard cycles should be clearly defined.
	Remaining Useful Life (RUL) definition and tests.
Vehicle-cloud integration	The set of data to be transferred by the BMS to cloud server for post processing or usage monitoring must be defined. The storage database format and duration of storage have to be defined.
	Standardisation of cyber security, privacy policy, type and duration of data storage in the cloud.
Second life applications	In addition to stationary applications, some more applications shall be identified as potential 2nd life applications for EV batteries.
	Application specific requirements and standards should be defined for the identified 2nd life applications.
	Standardization of communication protocols for various sub-components of 2nd life applications.
	Switching of 1st life BMS to 2nd life applications, without need of additional requirements or major modifications.
Data sheet specifications	The nominal battery test conditions and ratings should be standardized across manufacturers.
	Test procedures for obtaining data sheet parameters and the tolerances in the estimated parameter values should be standardized across manufacturers.
Open BMS platform	Requirements and standards should be defined for the development of open, flexible BMS platforms.

Table 2: Identified gaps in available standards for Battery management system

2.2.1 POSSIBLE STANDARDS FOR BMS FEATURE EXTENSION

OBD-II: This standard which is mandatory in internal combustion engine vehicles shall be extended to electric vehicles also for collecting diagnostics and usage history data for further analysis and post processing.

ISO 17826: This standard defines the things to be considered for implementing an interface for data transfer from a system to cloud environment. The data collected through OBD-II interface has to be transferred to the cloud platform for post-processing and storage. [31]

IEC 27018: This document establishes control objectives, controls and guidelines for implementing measures to protect information processed and stored in public cloud computing environment. [31] The diagnostics and usage history data collected through the OBD-II interface shall be transmitted to an external cloud-based platform for analysis, post processing and storage. Storing and processing such large data on-board may incur large computational and memory requirements [32].

ITU-T X.1631: The post-processed results and usage history data have to be stored in the cloud throughout the service life of the battery system. This data will be highly significant while deciding its eligibility for serving a 2nd life application. Hence considering the importance and confidentiality of this data, cyber security standards shall be adopted for batter application related cloud storages also [33].

IEEE P2413: For the above-mentioned processes like data collection, transmission, cloud based post-processing and storage, an architecture has to be developed for connecting the battery system, transmission medium and cloud platform in a network. Hence this IoT standard shall be adopted for battery system related cloud services [34].

ISO 11898: When implementing an EV battery system in a 2nd life application, carrying over the EV BMS also along with the battery pack brings in cost, time and complexity reductions. Since the communication protocol between subsystems in the 2nd life application may vary from that of an EV application, a bridging communication protocol is required which can communicate only the needed non-confidential information from the EV BMS. CANopen protocol defined in this standard could be a potential solution [35].

AEC - Q100: This generic standard defines the ways for studying the possible failure mechanisms in an IC based on quality check methods. With increasing use of application specific ICs in battery management systems, this standard shall be adopted for failure analysis of ICs used in BMS [36].

3 BMS Standardization for Functionality, Testing and Development

This chapter introduces BMS standard development potential from the context of hardware architecture, functionality, testing and diagnostics. Additional proposals for concurring to a trend in various aspects related to battery packs, recommendations for BMS development, creating convenience for second-life applications are elaborated.

3.1 Standardization potential of BMS hardware architectural solutions

A BMS has different functions to perform, such as electrical management, safety management, communication, improving battery usage efficiency and lifetime.

These tasks can be distributed among different subcomponents of a BMS:

1. Cell monitoring unit (CMU): The CMU measures cell voltage, temperature, and additional parameters on cell level and provides cell-level balancing.
2. Module management unit (MMU): Manages and controls a group of CMUs or a group of cells.
3. Pack management unit (PMU): It manages MMUs, makes decisions & state estimations, communicates with external systems and controls battery safety functions.

Depending on the way in which these sub-components are connected, the topology shall be distinguished as:

1. Centralized architecture: CMUs, MMUs & PMU are combined into one single printed circuit board (PCB), handling all the BMS functions. The PCB is directly connected to the battery cells. Centralized BMSs are simple and compact, but not suitable for high voltage systems because of wiring complexity and isolation issues.
2. Modular/master-slave architecture: MMUs are separated from the PMU PCB and are 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. Thus, in contrast to the centralized BMS topology, the PMU is connected indirectly to the individual cells in a modular arrangement.
3. 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 is further reduced [2].
4. Distributed BMS topology: Here, several stand-alone PMUs are present which 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. This topology offers maximum flexibility and scalability, but has also the highest complexity and costs, since a complete arrangement of CMUs, MMUs, and PMUs is required for each set of cells or supercells.

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 [37].

3.2 Standardization potential of BMS Functionalities and their Validation methods

This subchapter enumerates the functionalities to be performed by a BMS, rationalizes them and presents validation methods for them.

3.2.1 Cell voltage monitoring

The BMS should monitor the voltage across all the cells in the battery pack. The BMS should detect and react to monitored cell-voltages crossing the minimum or maximum operational limits specified by the cell manufacturer. Additionally, monitoring cell-voltages would support the BMS to perform other functionalities, such as:

1. Perform cell voltage balancing (see detailed in chapter 3.2.4).
2. Perform OCV measurement for SoC recalibration.

If cells are not operated under specified cell voltage limits, this could lead to cell degradation and accelerated aging. In an application with individual cells connected in parallel, the parallel terminal should be monitored as single cell voltage [38] .

3.2.1.1 Test procedure for protection against cell-voltage limit violation

The existing standard applicable for testing overvoltage and undervoltage protection functionality of a BMS, is ISO 12405-2 - Electrically propelled road vehicles -Test specification for lithium-ion traction battery packs and systems, of which chapter 2 focuses on high energy applications.

The test procedure for BMS performance, in the scope of cells being operated within cell-voltage limits is briefed below.

This test shall be conducted at room temperature. At all the cell terminals BMS measures voltages of each cell. For the tests, voltage of a cell is simulated/emulated at,

1. Nominal voltage;
2. Below minimum voltage limit and
3. Above maximum voltage limit.

Whenever the cell terminal voltages violate the upper or lower voltage limits, the BMS should immediately detect it and stop further charging or discharging of the battery by disconnecting with the power system. [10]

3.2.2 Current flow through battery pack monitoring

The BMS should monitor the current flowing through the battery pack. The BMS should detect and react to the charging or discharging current flowing through the cells crossing the maximum operational limits specified by the cell manufacturer. Additionally, monitoring the current flow would support the BMS to perform other functionalities such as,

1. avoiding thermal runaway caused by current flow above operational limits,
2. ampere hour counting for SoC estimation,
3. WH counting for SoE and
4. other SoX functions (detailed in chapter 3.2.7).

3.2.2.1 Test procedure for protection against current limit violation

The existing standard applicable for testing overcurrent protection functionality of a BMS, is ISO 12405-2 - Electrically propelled road vehicles -Test specification for lithium-ion traction battery packs and systems, in which chapter 2 focuses on high energy applications. The test procedure named as Short-circuit protection test in the above-mentioned standard is explained below:

Regarding the test procedure to validate this BMS functionality, using an external tester, initially the cell is charged with a permissible current and gradually the charge current is increased until it grows higher than the manufacturer specified limit. The same procedure is repeated in the discharging direction too. In both cases, the BMS functionality shall be observed.

These tests are repeated several times both in charge and discharge directions at various combinations of temperatures and cell terminal voltages. In all the combinations, the BMS should be able to detect the overcurrent situation and limit it to a maximum allowable value.

3.2.3 CELL TEMPERATURE MONITORING

The BMS should monitor the cell temperatures in the battery pack. The BMS should detect and react to monitored cell-temperatures crossing the minimum or maximum operational limits specified by the cell manufacturer. Additionally, monitoring cells temperature would support the BMS to perform other functionalities such as,

1. avoiding thermal runaway caused by operating cell above maximum temperature limits,
2. avoiding accelerated aging because of operating cells at temperatures higher than 40°C [39].
3. avoiding charging at low operating temperatures (specified in data sheet), which could lead to lithium plating which intern could lead to internal short circuit [40],
4. expecting capacity reduction during charging and discharging (due to raise in internal resistance at lower temperatures),
5. SoX functions (detailed in chapter 3.2.7) and
6. Thermal management (if applicable).

Cells in a battery pack operated at different temperatures would lead to inhomogeneous ageing of cells. Gradient between cells should be monitored and possibility avoided.

The BMS should continuously monitor the temperatures of critical points of the cells. If the battery pack is being provided with a thermal management system, the BMS can either actuate thermal management system control or send a 'cooling/ heating' request to the concerned system. This can help the cells to be operated within the allowed cell temperature limits stated in the cell data sheet, and avoid thermal runaway.

3.2.3.1 Test procedure for protection against temperature limit violation

The existing standard applicable for testing overtemperature protection of battery systems are ISO 12405-2, ISO 6469-1. [41]

The test procedure for a BMS to operate cells within cell-temperature limits is briefed below.

The BMS should detect the temperature and be able to evaluate whether or not the limits have been reached, and protect the battery system as per manufacturer defined specifications.

1. The cell shall be connected to a load and initially kept at room temperature.
2. It shall be operated with permissible continuous charge and discharge currents.
3. The battery system temperature shall be continuously increased at a rate of 1K/min until it reaches the maximum allowable temperature.

4. Then the cell shall be brought back to room temperature while still operating within permissible range of current flow. Then the temperature is reduced at the rate of 1K/min till it reaches minimum recommended operating temperature.

The same procedure shall be repeated by heating up or cooling down one or more temperature sensors to over and under temperature limits and the BMS shall still detect the temperature limit violations and limit the battery operation. [41]

3.2.4 Cell balancing

Cell balancing is homogenizing the series-connected cell voltages in the battery pack.

Cells in a battery pack could age differently compared to one another for the reasons mentioned in chapter 3.2.1, 3.2.2 and 3.2.3. An aged cell would reach minimum or maximum limits of operation earlier than a less-aged cell for discharging or charging respectively. In the presence of unevenly aged cells in a battery pack, the useable capacity of the whole battery pack is reduced.

3.2.5 Galvanic isolation between circuits working at different potentials

Galvanic isolation is the separation of electrical systems/subsystems by which non direct current can flow and may possess different ground potentials [42] [43] [44]. The functional sections of the BMS in a LV system or HV system the components of a BMS and depending on the application connected systems should be galvanically isolated. In a BMS, a subsystem of BMS or an external system would operate with grounds at different potentials. In electrical systems, components are galvanically isolated to avoid the flow of direct current between them. This is especially important in systems and subsystems with grounds operating at different potentials. Ground-loop currents constitute electrical noise that can interfere with the operations of either circuit. If the difference in ground potentials is sufficiently large, the resulting ground-loop current can pose a safety issue. [45] In a HV system, the magnitude of such ground-loop currents could get high enough to lead to life endangering situations. Ground-loop currents constitute electrical noise that can interfere with the operations of the circuits.

3.2.5.1 Test procedure for protection against insulation failure

The test procedure for insulation protection is intended to detect the insulation fault in between positive / negative terminals and ground irrespective of whether load is connected or not, is listed in standard ISO 6469-3, section 7.6. An adopted version of it is mentioned in deliverable, D2.5 "Development of reliability test procedures for EV BMS" [41], which is applicable for testing this BMS functionality.

The battery system is brought to room temperature and the insulation fault shall be simulated using a resistance. The test shall be executed for various combinations of operating voltages (U_{min}, $U_{nominal}$ & U_{max}). The BMS shall detect the insulation fault within a very short period (usually in milliseconds range) and execute manufacturer prescribed safety measures.

3.2.6 Data Communication

The communication interfaces are required for enabling data transfer between various subsystems present within a BMS (internal) as well as with other sub-systems (external) present in an application which the BMS is serving.

These interfaces should be flexible and universal for easy interfacing with microcontrollers and other components present in the network, which are likely to come from different manufacturers.

3.2.6.1 External interfaces

Controller Area Network (CAN) interfaces are widely adopted for communication between the BMS and other subsystems present in an application network. CAN interfaces are highly preferred for being highly universal, flexible and the ease of integrating components from different manufacturers.

The possibility and interface to log signals externally for diagnosis purpose is highly recommended. Presence of an USB interface to connect the BMS with an external PC for data logging and diagnostics purpose and OBD-II interfaces (in case of automotive applications) are common practices.

An additional interface shall be provided between the master module and insulation monitoring device in order to make sure that there is no insulation failure in between the high-voltage contactors (up to 1000 V DC) of the electric vehicle.

Interface to electromagnetic relays are provided through digital buffers. These are used to assure proper opening and closing of high-voltage terminals of the battery system. Additionally, these digital buffer interfaces also transmit control and feedback on the status of electromagnetic relays responsible for pre-charge and active discharge functionalities.

As the trend for reuse of an EV battery in second life stationary applications is gaining acceptance, attention should be paid on providing suitable bridging mechanisms for the EV BMS to communicate with various sub-systems that could be present in a 2nd life application, for which an EV BMS is not initially designed.

3.2.6.2 Internal interfaces

In a BMS, for the subsystems present in it, an important communication channel is between main controller and measurement modules. Both data transfer (from the measurement module to the control module) and control commands have to be communicated (from the control module to the measurement module).

Communications between sensors and control units shall be done through SPI or I^{2}C interfaces.
All the communication lines should be isolated from other data signal lines and power lines in order to avoid electromagnetic interferences.

3.2.6.3 Recommended protocols

Wired	Wireless	Other
BroadR-Reach	Smart Mesh dust network (IEEE 2.4 GHz)	Plastic optical fibre (POF)
CAN / CAN FD		
IsoSPI		

Table 3: Possible communication interfaces for a battery management system

The possible interfaces and communications protocols for embedded systems are listed in Table 3.

The CAN interface being a standardised and widely used protocol in the automotive sector should be used for communication in between the control units of the BMS.

Communications between sensors and control units shall be done through SPI or I^{2}C interfaces.
All the communication lines should be isolated from other data signal lines and power lines in order to avoid electromagnetic interferences.

A diagnostic interface could be provided to allow data logging from BMS. CAN interface is widely accepted. Interface to electromagnetic relays should be provided through digital buffers to assure proper opening and closing of high-voltage terminals of the battery system.

3.2.6.4 BMS information to be communicated

The battery parameters acquired and computed are communicated to the higher-level system. They include:

1. Statistics of cell (minimum, maximum and mean)
    a. Cell voltage.
    b. Cell Temperature.
    c. Current flow.
2. SoC.
3. SoH.
4. SoP.
5. SoF.
6. BMS status.
7. Battery disconnecting unit status.
8. Battery pack cells configuration (no. of cell in parallel and series, and total).

3.2.7 SoX functions

This chapter deals with the definition of various state estimation parameters like State of Charge, State of Health, State of Power and State of Functions. The reliability of such estimated pack parameters depends on the inconsistency in the behavior/aging between the cells present in the battery pack.

3.2.7.1 SoC

The State of Charge (SoC) of a battery is the measure of the actual level of charge it contains relative to its maximum capacity. It can be represented as ratio between actual stored charge Q_{actual} and the maximum capacity Q_{max}.

$$\text{SoC} = \frac{Q_{actual}}{Q_{max}}$$

The maximum capacity can be defined as the charge stored inside a cell when it is in its fully charged state. A fully charged state can be achieved by charging it with constant current (CC-mode) until the upper cut-off voltage is reached and then continuing with constant voltage charging (CV-mode) until the charging current falls below a fraction of 1C charge current (e.g. C/100) [46].

3.2.7.1 SoH

The state of health (SoH) is an indicator of degradation a battery as undergone compared to a new battery. The SoH of a battery pack could be estimated using various factors. The most widely accepted methods are based on battery capacity and impedance. A battery for a particular application can be considered as it reached its end of life when its capacity falls below 80% of its beginning of life capacity and when its impedance nearly doubles (200%) when compared to its beginning of life impedance [47].

The fall in capacity affects the maximum amount of energy that can be stored and delivered by the battery system while the rise in impedance affects the maximum deliverable power capability. The SoH is represented either in numeric range of (0-1) or in percentage (0-100) %, where 0 or 0%

indicate that the battery has reached its end of life, while 1 or 100% indicate that the battery is in its beginning of life.

3.2.7.2 SoP

Similar to maintaining permissible SoC limits, maintaining the power limits of a cell should also be one of the main tasks of a BMS, when it comes to high power demanding applications. Power limits tell us how much power shall be drawn or fed into a cell without violating any of its operating limits (voltage, current & temperature). [48]

Operating cells at higher power levels will accelerate aging. The BMS should compute the optimized power limits in accordance with the application expectations considering safety, power performance and longevity.

3.2.7.3 SoF

The state of function (SoF) is a parameter stating whether a battery system can serve an application or not. It combines SoC, SoH, SoP and also load conditions to estimate the power capability of a battery system to serve that particular application.

SoF is an estimate of continuous or peak power output capability based on load and battery state. SoF shall be defined either in digital format [0 or 1] or in continuous format 0~1. "The digital definition of SoF shows whether the battery has sufficient power capability to carry out a specific function of the application and the continuous one gives the current battery power capability contrast with the primary power capability." [49] Here, continuous format provides more insight about the extent to which the application demand is satisfied.

3.2.7.1 SoE

The state of energy (SoE) of a battery is the parameter stating the ratio between remaining energy ($Eactual$) and maximum available energy of a battery ($Emax$). [50]

$$\mathrm{SoE} = \frac{E_{actual}}{E_{max}}$$

SoE estimation is critical for energy optimization and management tasks, like range prediction in EVs, backup time estimation in stationary applications etc. Both SoE and maximum available energy are dependent on the ambient temperature, operating discharge/charge current rate and cell aging level. [50]

3.2.8 Controlling contactor switching

Monitoring the status and controlling the switching of the high voltage battery pack contactors is one of the critical tasks of a BMS, failure of which may lead to electric shock or other safety hazards. For safety reasons, the battery pack should completely disconnect itself to external charge and discharge electrical connections, in case of battery safety parameters are violated.

The switching of contactors connection with load shall be achieved through relays which should be of 'normally-open' type. This is because, if the BMS contactor switching losses power due to any failure, then the contactor terminals are automatically de-energized, and the pack is disconnected from the load.

3.2.9 HIGH CURRENT PROTECTION FUSE

A high-current fuse should be included in the design to protect the battery pack from charge or discharge current flow outside the range of the safe operation limits specified by its manufacturer. The fuse could be designed to be at single cell, or at each module, or at battery pack level.

3.2.10 ADDITIONAL FEATURES

3.2.10.1 Thermal management

Thermal management is an important aspect for battery packs, in order to assure long battery life as well as for safety concerns. It is generally recommended to operate lithium-ion cells within a temperature range of 10-40 °C for long life.

Either BMS should control thermal management functionality or send relevant information to the higher system to perform thermal management.

3.2.10.2 Reverse polarity detection

3.2.10.2.1 HV connections

Reverse-polarity connection can occur in circumstances such as installation of a new battery, reconnection of the original battery after repairs etc. The BMS should be able to detect a reverse polarity connection whenever the battery contactors are closed, before supplying the connected load.

Operating a battery system with reverse polarity fault can lead to short circuit, damage to internal electronics or even electrical shock. A reverse polarity sensor can be installed to monitor the HV contactors and communicate its polarity status to the Master module of the BMS.

For low voltage systems up to 24 V, the reverse-polarity test is specified by the ISO 16750-2 standard. For high voltage systems, polarity reversal testing can be done according to IEC 60060-1 standard.

3.2.10.2.1 Cell level

For low voltage applications, cell level reverse polarity detection shall be implemented similar to that of in HV applications. These protections shall be done both at hardware and software levels.

3.2.10.3 Short circuit detection

It is not desirable to charge or discharge a battery system after safety fuse is blown out. The BMS should detect this scenario and disconnect the battery pack to external power systems of the application.

This scenario shall be simulated by opening a switch creating an open circuit. The battery system is operated at various voltage levels and at combinations of various charge/discharge scenarios. In all these cases, the BMS should be able to detect the activated fuse and take measures prescribed by the manufacturer. The battery usage is limited or affected, and it should return to normal operation only after an intervention of service personnel.

3.2.10.4 EMC compatibility

The ICs used in EV BMS are susceptible to electromagnetic interference from on-board electronics and other components of the powertrain. These interferences when picked up by the connections between the ICs and the control unit, can cause malfunction of components and can lead to safety issues in EVs.

The existing standard applicable for EMC compatibility test of BMS components are IEC-62132-4, ISO11452-2 and ECE Regulation 10. The design factors to be considered for reducing the generation and influence of electromagnetic interferences in PCBs are listed in [51].

3.3 Standardization potential of tests for BMS

This sub-chapter is a compilation of different test standards and their adoption to BMS tests.

3.3.1 Environmental Tests

3.3.1.1 Humidity, dust and water tightness test

These tests are intended to study and validate the robustness of the BMS when operating under severe environmental conditions like high amounts of dust, high levels of humidity etc. The possible failure modes are electrical malfunction(s) caused by moisture (e.g. short circuit within PCB board components when it gets in contact with water or leakage current triggered in the PCB components due to presence of high moisture).

Accumulation of dust over time could insulate the conductive parts, increasing their resistance and heat losses. This causes overheating of PCB components which may lead to malfunction or even failure in worst cases.

3.3.1.1.1 Test procedure

The tests can be performed as per the procedure stated in IEC 60068-2-30. The BMS is maintained at full operating mode with load connected according to ISO 16750-1 throughout the test sequence.

In practical applications, the BMS will be protected from direct contact of environment by using an additional housing. Depending upon the design, there could be a dedicated housing for the BMS components alone or the battery pack housing itself is enough to protect the BMS also. The housing will protect the BMS from ambient humidity, water and dust [3].

3.3.1.2 External electromagnetic radiation test

The BMS must be designed such that the amount of electromagnetic emission it causes is minimal. It should also have good immunity and isolation from any external electromagnetic noises.

The BMS should ideally have low levels of electromagnetic emissions as these may disturb the operation of devices or components surrounding it.

The reference and applicable test procedure are: **ECE Regulation 10.05.**

Additionally, the housing plays a major role in shielding the BMS from external electromagnetic noise as well as in reducing the electromagnetic radiation originating from the BMS. So, it is recommended to conduct the above-mentioned tests on the BMS with the housing included.

3.3.1.3 Temperature change test

The references and applicable standard are: IEC 60068-2-14. The BMS should be able to withstand the effect of thermal stress without any damage to its components or impediments to operation. The tests are briefly introduced in the following subchapters 3.3.1.3.1 and 3.3.1.3.2. These tests are elaborated in detail in the public deliverable, D2.5 "Development of reliability test procedures for EV BMS". [41]

3.3.1.3.1 Gradual temperature change

The BMS wiring is disconnected and its ambient temperature is varied gradually between its maximum and minimum limits at a rate of 1K/min. Then the BMS is brought back to room temperature and tested at full operating mode with a load connected to assure that all BMS functions are performed correctly.

3.3.1.3.2 Rapid temperature change

The BMS wiring is disconnected and the ambient temperature is varied quickly between its maximum and minimum limits within 30 seconds transition time. Then the BMS is maintained at the reached limits for 30 minutes to achieve temperature stabilization. This cycle is repeated 100 times. Then the BMS is brought back to room temperature and tested at full operating mode with load connected to assure that all BMS functions are performed correctly.

3.3.1.4 Mechanical shock & vibration test

3.3.1.4.1 Mechanical shock

The BMS shall be prepared with all external and internal wiring connected. The test shall be performed according to the procedure stated in ISO 16750-3. If the direction of shock occurrence in the vehicle is known, the test shall be applied in that direction. [52]

If the direction of the effect is not known, the shocks shall be applied in all six directions (±X, ±Y, ±Z) according to parameters mentioned in the following table.

Parameter	Value
Acceleration	500 m/s^2
Duration	6 ms
Test temperature	Room temperature
Number of shocks	10 at each of the six directions

Table 4: Test parameters for mechanical shock test

3.3.1.4.2 Mechanical vibration

This test is intended to check whether the BMS experiences any malfunctions and/or breakage when exposed to vibration. The vibration that BMS experiences shall be externally from rough-road-driving conditions or internally from the powertrain vibrations.

The BMS shall be maintained at electrical operation with HV-load connected. The vibration test shall be carried out according to ISO 16750-3 / IEC 60068-2-64.

The BMS shall be exposed to random vibrations in all three directions (X, Y, Z) using the following parameters:

- RMS acceleration: 27,8 m/s^2
- Frequencies: 10-2000Hz
- Duration of applied vibration: 8 hours/axis.

No visual or functional defects shall be observed at the end of the vibration test.

3.3.2 Additional tests for BMS Validation

In addition to the test procedures intended for validating the safety and performance functionalities of a BMS that have been stated in the sections above, environmental tests should also be performed in order to validate the robustness of the BMS when operating under severe ambient conditions.

3.3.2.1 Fault injection test

Using a Hardware in the loop (HiL) testbench, various faults shall be injected into the system and the response of the system should be tested. The fault detection time and response time for a give fault should be recorded, mainly for functionalities described in Chapter 3.2 and other safety critical functionalities. This provides an overview of BMS correctness and responsiveness.

3.3.2.2 SoC estimation performance test

There are several methods meant for keeping track of the actual charge level known as SoC algorithms. This SoC algorithm is specific to the BMS manufacturer, while for benchmarking purpose shall be compared with SoC from the external tester which is based on integrated current log. This method is known as coulomb counting.

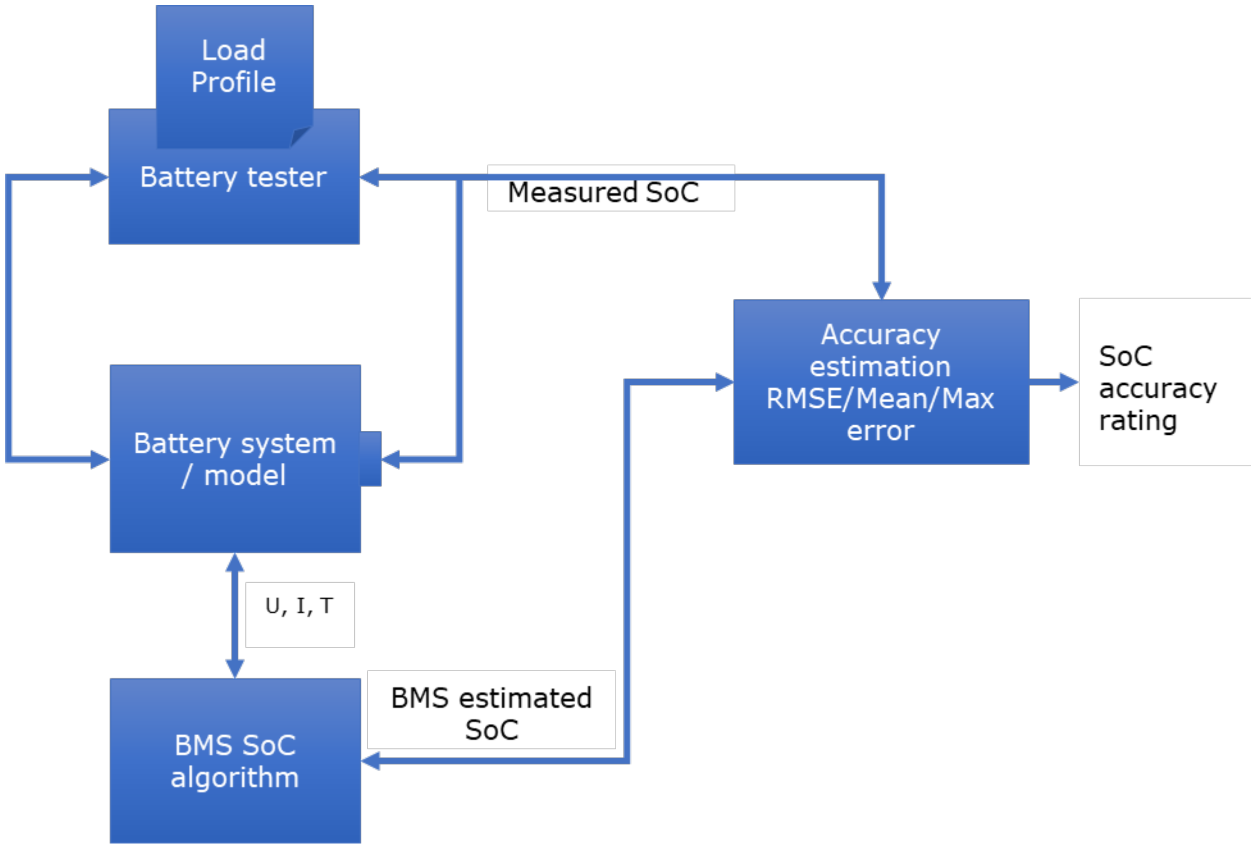


Figure 1: Test setup for SoC estimation validation [46]

Battery tests would be expected to be equipped with an accurate current sensor. Thus, for short duration tests, SoC calculation from current integration will be accurate. Due to the nature of an integration-based estimate however, the integration error will accumulate which results in high deviation in the estimated SoC values. It is recommended to recalibrate the cell SoC based on its OCV, when the cell is adequately relaxed.

The maximum cell capacity and actual charge level are strongly influenced by the operating conditions such as temperature, load current. In a cell internally losses may increase due to aging.

Here, in order to evaluate the accuracy of BMS SoC estimation, it shall be compared with the residual charge measured by an accurate battery tester. The battery system or an accurate model which could simulate the battery performance shall be used for this test [46]. The test procedure flow is represented in **Figure 1**.

The load profiles used for cycling the battery system shall be chosen such that they cover different driving scenarios, enabling the estimation of SoC algorithm accuracy irrespective of the driving conditions/styles. C. Campestrini et al proposed three types of load cycles, namely low dynamic, high-dynamic and long-term drive profile [53]. These profiles shall be applied at different temperatures and SoC levels, after which the residual capacity is measured by the tester and compared with the BMS logged SoC to judge the quality of the BMS algorithm.

3.3.2.3 SoH estimation performance test

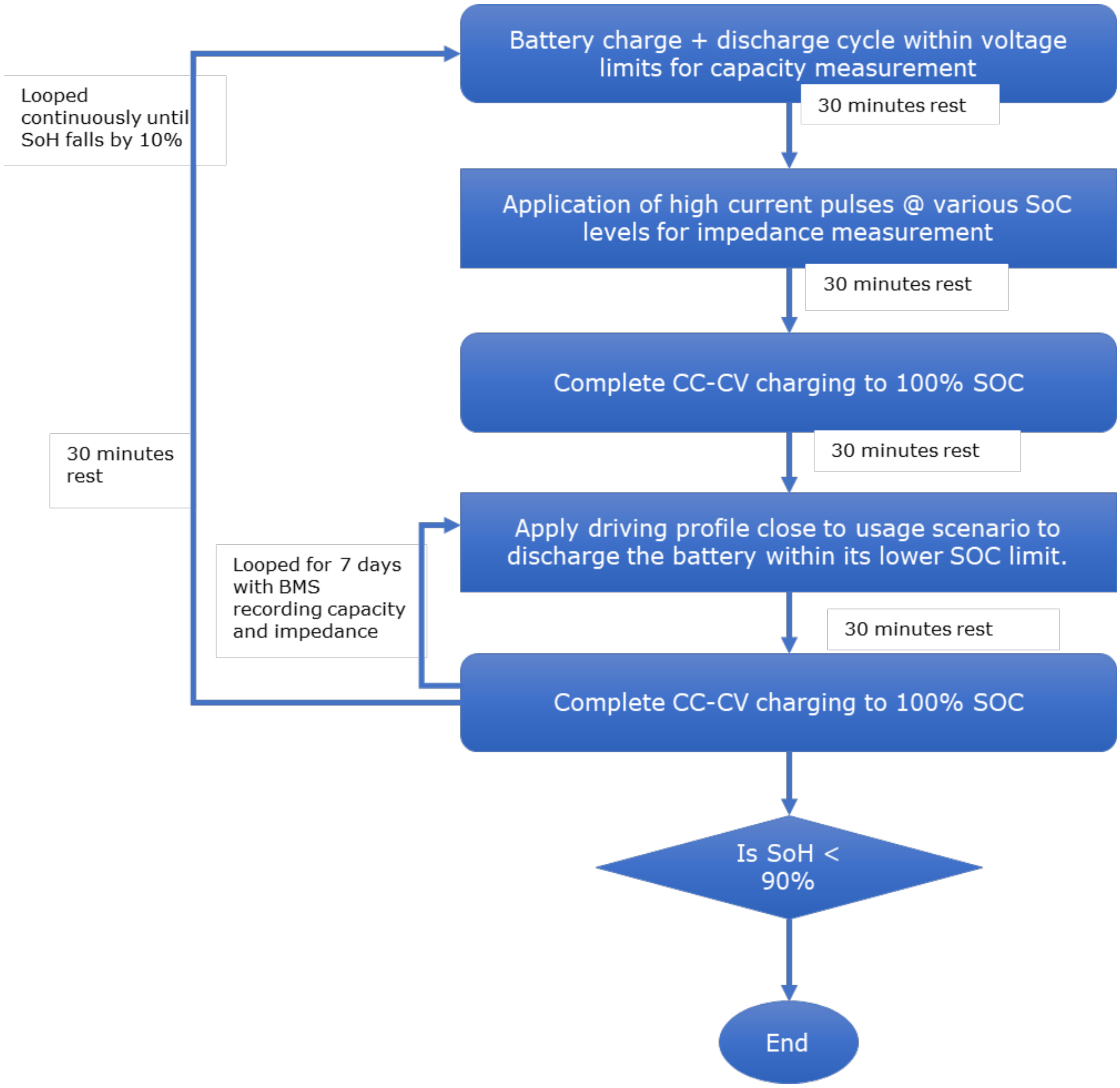


Figure 2: Test setup for SoH estimation validation [54]

In order to evaluate the accuracy of the BMS SoH estimation, it should be compared with the capacity, and internal resistance or impedance estimations/measurements recorded by an accurate battery tester [54]. The battery system or an accurate model which could simulate the battery performance shall be used for this test.

Both the battery system and the simulated battery should be cycled with a long-term load profile like dynamic test profile, UDDS, FUDS, real world recorded application specific load cycle, or a reference drive cycle used by the BMS manufacturer. The verification shall be done by comparing the modelled values and the SoH values which are being presented by the BMS.

The overall test procedure mentioned is illustrated in **Figure 2**. In addition to this, the BMS is disconnected and using the external tester, the capacity and impedance of the tested battery are measured.

The impedance shall be measured either by performing Electrochemical Impedance spectroscopy or by applying high current pulses at various SoC levels. The capacity shall be measured by performing a standard complete (charge + discharge) cycle.

Since both the capacity and impedance depend strongly on temperature, these measurements shall be done at different temperatures or at least in the temperature range where the application will be mostly operating. Comparing these measured values with the BMS estimated values would give a good evaluation on the reliability of BMS estimated SoH.

3.3.2.4 SoP estimation performance test

This test is intended to determine the dynamic power capability and the ohmic resistance of the battery system. The aging of the cells used in the battery system impacts the ohmic resistance which in turns limits the maximum deliverable power. Hence the BMS should be able to track the change in ohmic resistance to accurately estimate the state of power of the battery system.

3.3.2.4.1 Pulse power characterization profile

The test applies a sequence of charge and discharge constant-current pulses which are within the range of the maximum rated pulse currents specified by the cell manufacturer. The test sequence is listed in **Table 5**, with current magnitude and duration.

Time Increment (s)	Time cumulative (s)	Current (A)
0	0	0
18	18	Imax
40	58	0
10	68	-0,75 Imax
40	108	0

Table 5: Pulse power characterization profile. [47]

These hybrid pulses shall be applied at various SoC levels to determine the discharge pulse power and regenerative charge pulse power capabilities of the battery system without any of the safe operating limits getting violated.

A sample applied HPPC current profile and the corresponding voltage response would look like in the **Figure 3** and **Figure 3**. The positive current denotes the discharge pulse and the negative current denotes a charge pulse (from regenerative braking). The magnitude of the applied pulse current shall be reduced if required, so that the cell stays within the manufactures specified voltage limits.

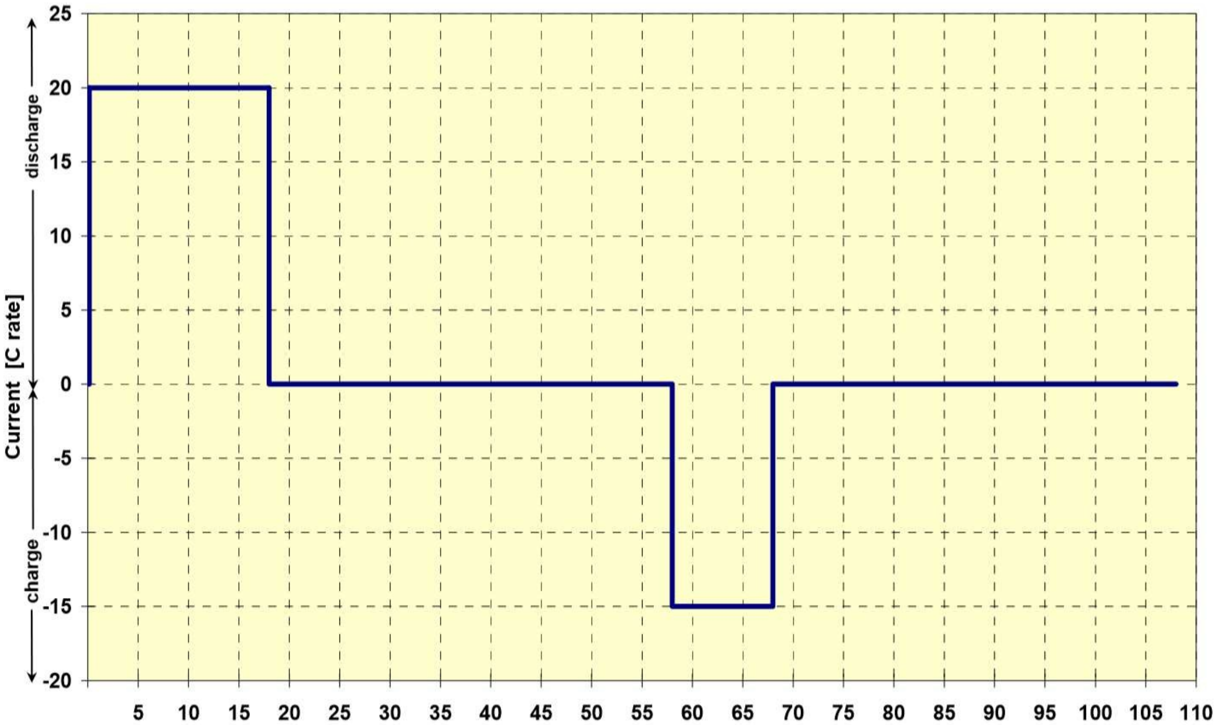


Figure 3: Pulse power characterization profile-current vs time [s] [55]

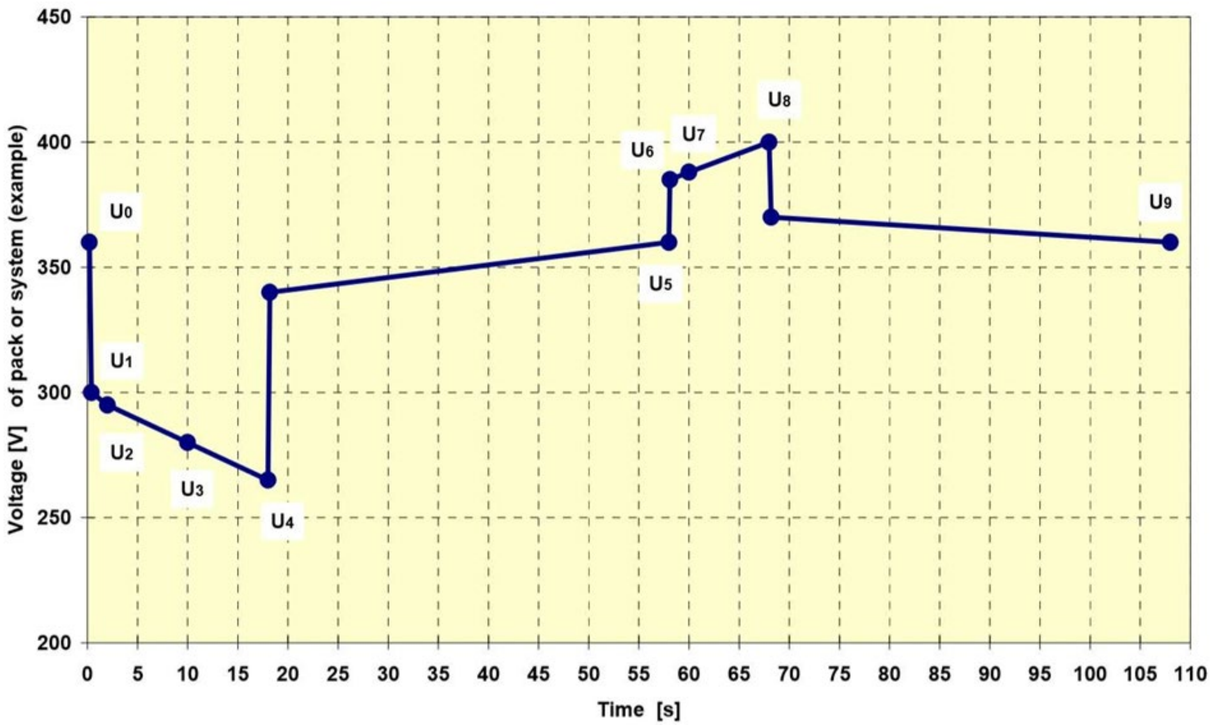


Figure 4: Pulse power characterization profile-voltage vs time [s] [47]

3.3.2.5 SoE estimation performance test

There are several model based, neural network based methods for keeping track of the actual energy level known as SoE algorithms. This SoE algorithm is specific to the BMS manufacturer. For benchmarking they should be compared with SoE from the external tester, which is based on the residual energy left in a battery after a dynamic load cycle. The test setup is identical to test presented in subchapter 3.3.2.2, 'SoC estimation performance test:'. The test procedure follows similar procedure to **Figure 1**.

The load profiles used for cycling the battery system should be chosen such that they would cover different load scenarios, enabling the estimation of SoE algorithm accuracy irrespective of the power demanding conditions. K. Mamadou et al proposed two types of load cycles, namely soft and hard dynamic stress test profile. [7] These profiles shall be applied at different temperatures, after which the residual energy is measured by the tester and compared with the BMS logged SoE to judge the quality of the BMS algorithm.

3.3.2.6 Maximum available energy test

The test procedures for estimating maximum available energy as a function of temperature and discharge/charge current rate are stated in standards ISO 12405 and IEC 62660-1.

1. The battery is brought to full charge and stabilised at a desired temperature,
2. then it is discharged at a current rate until its lower cut-off voltage is reached,
3. this test is repeated for various combinations of current rates and temperatures.

The delivered energy is estimated in each case. The results of these tests shows the Maximum available energy of the battery pack [10] [56]

3.4 Recommendations for BMS development

In addition to the generic requirements to be standardized for a BMS, additional functionalities are recommended in the following sub-chapters.

3.4.1 Shutdown on potential physical damage

The BMS should detect damage or read-in 'damage' signal from the higher system-in-hierarchy. The BMS should disconnect the electrical connection to external power systems (load/charger).

3.4.2 System reset on detection of abnormal behavior of main controlling component of the BMS

When the BMS detects that its functionality or a component exhibiting abnormal behavior, the BMS should reset that particular functional component or the BMS. It should depend on the application's operating mode and the severity of behavior.

3.4.3 Tamper proofing BMS

Hardware and software of the of the BMS should be made tamper proof. Making the BMS tamper proof and BMS being able to detect it, would improve the safe operation of the BMS. Further improvements to operational safety include making the BMS sensitive to tampering.

3.4.4 Vehicle And Cloud Integration

Monitoring the usage history of a battery system is very important for estimating remaining useful life, warranty issues and suitability for specific 2nd life applications. The following parameters could be tracked. The count and modes of battery pack been operated (but are not limited to):

1 outside certain limits.
2 type of charging cycles (low C rates, fast).
3 critical modes of operation.
4 critical load demands.

Storing and analysing this data on board for life-time would be less practical. A cloud-based solution could be adopted. But factors like deciding which data should be stored on cloud, duration of holding the data and privacy could be an impediment to the viability of this solution.

The interface through which the application communicates, the database format for data storage shall also be decided according to application specific requirements. Irrespective of the application, the bidirectional data transfer should be encrypted, and cyber security measures must be taken to guard the data stored in the server.

3.4.5 Consolidation/virtualization of BMS functions on central vehicle control units/platforms

3.4.5.1 Requirements of current BMS architecture

With increasing use of advanced software features in EVs for improved performance and user experience, the expectation of features offered by BMSs keeps mounting. The BMS must handle more critical functionalities like safe monitoring and maintenance of operating limits (voltage, current, temperature etc.). Additionally, it must also take care of other non-critical functionalities like state estimation (SoC, SoH, SoF, SoP and SoE).

Using dedicated BMS hardware would increase the cost pressure, hence standardization/unification of BMS components for universal coupling will be a good solution. This will in turn be helpful in satisfying the increasing requirements for BMS hardware and software functional development norms.

Very complex algorithms are required to perform long term model-based analysis like aging assessment, abuse monitoring etc. The BMS should also be open to third-party functionality integration for improving application performance and safety over its lifetime. Given the trend, the implementation of cloud solutions for advanced data processing and storage could also be adopted. Designing and developing a BMS within cost boundaries, which can accomplish all the above-mentioned tasks seems challenging.

3.4.5.2 Description Virtualization idea/principle

The idea of BMS virtualization is to replace the BMS master control module by a virtual machine which runs directly on the vehicle control unit (ECU). By doing so, the dedicated BMS hardware can be limited to slave control modules for monitoring and measurement alone, which in turn reduces the cost, complexity and space occupied by the BMS hardware.
Most of the modern EVs are equipped with multicore platform vehicle control systems, for which handling complex state estimation algorithms wouldn’t be an issue. This virtual machine can be monitored by a hypervisor (A real-time operating system like PikeOS from SYSGO). This virtual machine can be made capable of running on external PCs too for simulation and development purposes.

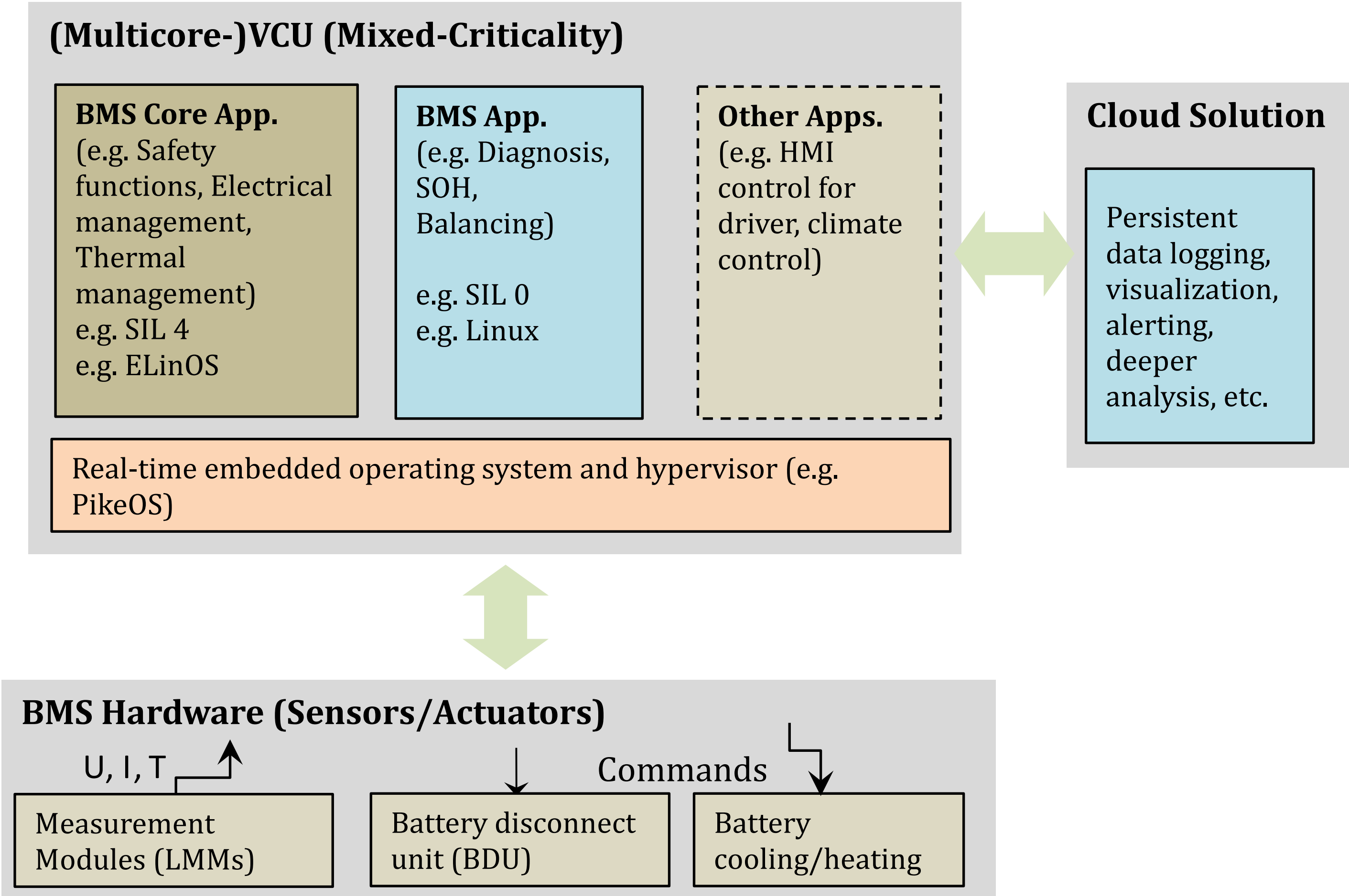


Figure 5: Possible Architecture for BMS Virtualization

3.4.5.3 Benefits of BMS Virtualization

The first and foremost benefit of BMS virtualization is the reduction in dedicated BMS hardware, as we need only measurement and monitoring BMS modules. This in turn reduces the size, cost and complexity of the BMS hardware.

Advanced model-based algorithms can be easily integrated through additional virtual machines on the VCU platform without additional modification in BMS memory or processing hardware. This virtual BMS can be used as a development tool (e.g. simulation building block).

Parallel running of applications with varying criticalities and safety level ratings is achieved the through software isolation principle. This feature facilitates the process of achieving safety certifications.

3.4.5.4 Additional requirements on BMS hardware

Since the BMS control module (Master) is virtually moved to the VCU, the measurement modules (Slave) and the battery disconnect unit should be enhanced by equipping them with a dedicated microcontroller to communicate with the virtual machine master module.

3.4.6 Open-source BMS platform

An open-source BMS would be a generic BMS (and may include/offer specific functionalities additionally) of which hardware and software are developed in collaboration with different development bodies, which could be distributed or redistributed. In an effort to increase collaboration across various development entities and increase market share, it could be considered to have an open-source BMS platform.

An open and flexible BMS platform should be defined with a basic structure upon which each BMS manufacturer can add their hardware and software functionalities to build application specific BMS. Existence of such platform can enable easy integration of 3rd party functionalities (e.g.: Complex state estimation algorithm, safety enhancement functionality etc.) and save lot of development time which would drive down the BMS cost too. [56]

3.5 Agreeable Conventions

This chapter is intended to mention some aspects of BMS functionality where a unified single convention has not been agreed upon yet. The factors listed in this chapter are still specific to BMS manufacturer or application. Unification and standardization of these parameters are highly significant for development of a flexible BMS hardware and software platform enabling easy integration of BMS subcomponents and functionalities from different manufacturers.

3.5.1 Current flow direction sign

From BMS perspective and battery, the *discharge current* is signed negative and *charge current* is signed positive. While communicating with our systems, this convention can avoid a misunderstanding. The unanimity is also followed for *coulomb counting*, as it is the parameter of dependence for SoC estimation through coulomb counting. It is convenient while integrating 3rd party state estimation algorithms, safety functions, and new measurement sensors into an already existing or an open BMS.

3.5.2 BMS error data logging

The usage history, abuse handling, error codes generated due to malfunctioning of hardware/software functionalities shall be recorded in a non-volatile memory of the BMS. This information will be useful for diagnostics and post application life analysis.

3.5.3 Dynamic monitoring rates for Applications

The sampling rate should be adjusted to the application so that no maximum peak values are missed out, but it should also be ensured that these peaks shouldn't result in memory overflow.

Any irregularities in system performance that can be captured through measurements shouldn't be missed out due to the measurement resolution or sampling rate. The irregularities can be identified by continuously monitoring the gradient of the monitored parameters with respect to the sampling time.

Any sudden unexpected spike in the gradients should be treated as irregularities and the sampling rate has to be increased accordingly to record the complete behavior.

The same concept shall be implemented while monitoring the cell voltages, currents and temperatures when nearing the permissible operating limits.

3.5.4 Data formats

The data format in which the measured signals are transferred between the BMS components as well as with external systems has to be standardized in order to avoid any misperception in-between systems from different manufacturers or when integrated with 3rd party functionalities.

3.5.4.1 Cell voltages

Generally measured cell voltage values are digitised and before being transferred to control modules are multiplied with a scaling factor instead of transferring them as floating-point values. This is done for memory management reason as well as for not losing any integer round off accuracy. This scaling factor should be unified and standardized.

3.7 V should be represented as 37000 [100 * micro Volt].

3.5.4.2 Cell temperatures

In addition to unification of the multiplication scaling factor, the unit of cell temperature must also be standardised in order to avoid any misinterpretation between functionalities or components which make use of measured temperature.

25 °C is 298.15 K, it should be represented as 29815 [centi Kelvin].

3.5.4.3 Battery pack voltage

800 V should be represented as 800000 [mV].

3.5.4.4 Battery pack current

200 A should be represented as 20000 [mA]

3.5.4.5 SoC, SoH

The representation of state estimation parameters like SoC, SoH etc. are made either in scale (0-1) or (0-100) % scale. This must be standardised in order to avoid any misinterpretation between functionalities or components which make use of the state estimates.
For scale 0 to 100, 50.55 % should be represented as 5055 [100 * SoX percentage].

3.5.5 Voltage and current measurement synchronization

Both the voltage and current measurements should be in synchronization with each other. Such synchronized voltage and current measurements are important for BMS for estimation of power parameters. A deterministic skew between voltage and current measurements could be allowed. [57]

3.5.6 Specifications from cell manufacturers

The parameters in the specification documentation from cell manufacturer should follow a definite standard to parameterize them. The test conditions, tolerances, test procedures followed, and termination conditions, definition of standard cycle etc. must be standardized.

4 BMS STANDARDIZATION FOR INTERFACES TO SUPPORT SECOND-LIFE USE CASES OF BATTERIES

This chapter initially discusses the factors that should be considered while estimating the remaining useful life of a battery and the collection of usage history data through OBD-II interface for further post-processing.

Then a scenario of integrating an EV battery system (battery pack + BMS) into a 2nd life stationary application is assumed, and the challenges faced, and possible solutions are also described. Finally, since a 2nd life application may not require all the information an EV BMS has, a set of basic information that the BMS must share are also listed.

4.1.1 Defining End Of Life

Even though the interest in using EVs is growing in recent years, in spite of considerable improvement in battery technology as well as battery monitoring system reliability, the range anxiety and question of remaining battery life still exists in users. This is because although SoC, SoH and distance to empty estimates are displayed to the user while starting a car, its reliability depends on the driving style and ambient conditions too.

Prognostics should be sub-divided into short term and long-term prognostics. Short term prognostics mostly deals with real-time information like battery charge, temperature and sudden variations etc. Other prognostics tasks are to make sure that the user is informed about any malfunction before it leads to hazard. Long term prognostics focuses on estimation the SoH or RUL of the battery pack.

Different methods of estimating and representing RUL exist. One way is to define RUL as the length of time from the present time to the end of useful life. [58] Second way is to define RUL as the number of cycles the battery can be operated from present time to the end of its useful life [59]. This way of representing RUL should be standardized and a unified practice of representation is recommended. Since definition of a standard cycle is still an open topic, defining RUL in terms of time period should be more meaningful from a user´s point of view.

While estimating the RUL of a battery pack, in addition to estimating its full range performance, the performance required from it and its operating environmental conditions should also be considered. These history of usage data can be collected through the OBD-II provision and transmitted for external post processing.

For example: If a person owning an EV with 300 Km range at full charge, drives only 100 Km every day, he can still use his car even if the pack capacity reaches 80% of its initial value. After assuring through post processing and OBD-II diagnostics that the battery pack can still serve the EV application without and safety concerns, in this case the pack can still deliver a full charge range of 240 Kilometers even if it has reached its end of life as per SoH definition (<80% of initial capacity).

Even in the case of long-distance driving needs, just the number of charges increase. Hence, the user doesn’t have to replace the battery pack soon reducing the cost of ownership as well as reducing the warranty costs for the EV manufacturer. [60]

In addition to RUL estimation based of driving profile, recommendations regarding driving style, optimal charging (avoiding unnecessary quick charges) can also be given to the user in order to reduce the faster degradation of the cells in battery pack.

4.1.2 OBD-II INTERFACE

The OBD standard was introduced in the early 90s in USA and the OBD-II standard spread to Europe in the early 2000s. Since then the vehicles manufactured contained an OBD-II plug. It´s currently mostly being used by service technicians, who can use it to connect an OBD reader/logger to evaluate the status of all functionalities offered by a vehicle. After 2008 the standard of implementing CAN protocol for OBD-II interfacing is followed. Since all the electronic units in EVs are connected by CAN, this is an added advantage.

In case of an EVs battery pack status, information like pack SoC, SoH, voltage, current, available energy, distance to empty, voltage and temperature differences between cells in pack etc. can be collected via OBD-II server based mobile applications. Additionally, history of usage like number of fast charges and normal charges made, driving profile, instant of abused usage etc. should also be retrieved through OBD-II via CAN messages.

Collecting, processing and storing all the history of usage data on board turns out to be highly computationally, demanding and complex, besides putting high demands on memory performance. Hence generally the Real-time CAN data collected through the OBD-II port is transmitted to an external network for performance analysis and storage. A separate micro-controller can be used for requesting, collecting and transmitting data through the OBD-II port.

In addition to this state monitoring feature, some more critical units in the EV powertrain should also be carefully monitored because failure or malfunction of these critical units may lead to reduced product life time or even to a hazard in worst cases. Hence, an on-board diagnostics (OBD) feature would be very handy for monitoring not only the critical units, but also in logging/transferring state estimation related data for further post processing purposes.

4.1.3 INTERACTION WITH EUROPEAN INITIATIVE FOR SUSTAINABLE BATTERY REGULATION

The European Commission wants to support the use and manufacturing of batteries in Europe. As part of its initiatives it studies the possibility for sustainable batteries on the European market. Emphasis is on the energy use what results in a carbon footprint of the battery. Extending the battery life is an important way to lower the carbon footprint. The propositions for requirements are given in the task 7 report of the 'Preparatory Study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage under FWC ENER/C3/2015-619-Lot 1'. [62] The BMS can play a key role in giving confidence in the remaining battery quality. The current proposition has three impacts on the BMS:

- obligatory partially open data from the BMS
- a possibility to update the BMS for second life applications
- a standardised BMS data connector.

The open data comprises similar items as in this Everlasting report like the number of charges and fast charges, the ampere hour throughput and kWh throughput, occurred errors and negative events. However, to follow a battery's lifetime counters are proposed to follow up e.g. the temperature and voltage. This information must be given on module level within the battery pack.

A special connector apart from the OBD connector is proposed since a battery can be taken out of the electric vehicle and still the open part of BMS information has to be read.

It is possible that the BMS cannot suitably work after repurposing the battery. This can be related to the SOC determination algorithms but also due to the cell balancing strategy. In these cases, the hardware can be correct but the firmware not. Therefore, an upgradability of the BMS' firmware is prescribed. An additional advantage may be that no new UN 38.3 test is needed. However, only if it can be ensured that the functional safety is not endangered.

4.1.4 Communication protocol for second life applications

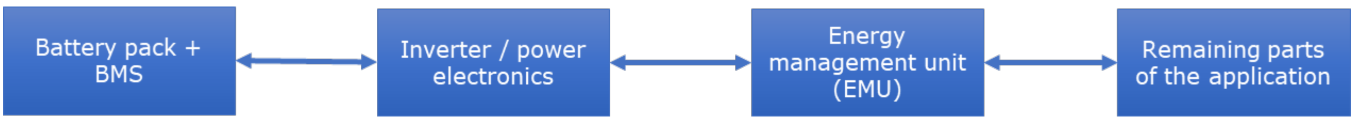
It is recommended to consider the factors explained in the section above while deciding on whether or not the EV battery can serve the EV's demand requirement. If this is not the case, it should be used in a 2nd life application. Once the decision has been made to use it in a 2nd life application, the first choice of it would be a stationary storage application (grid storage, home storage etc.), since weight and space limitations for energy storage are less intensive than in EVs.

Some modifications have to be made on the battery system as well as the BMS before reusing for a different application. Direct reuse of the battery modules is preferred as it is cost saving, while at the same time reducing the risk of failure during reassembling. Since this work focuses on the BMS, we address the transformations needed in the BMS alone. Unlike the direct reuse of battery modules, the direct reuse of an EV BMS for a stationary application is limited by various factors like the difference in the architecture of other connected devices connected in the network, the communication protocol and the extent of accessing the confidential information inside the BMS.

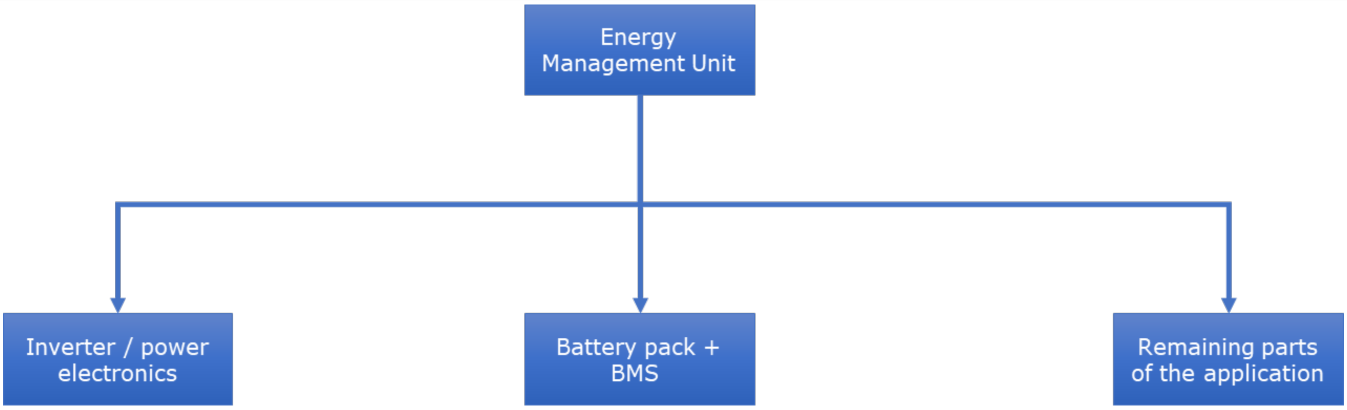
The confidential information includes state estimation algorithms, security parameters etc., which the EV manufacturer may not prefer to access or modify. If these factors are considered in advance while designing the EV BMS itself, then direct reuse of both battery module and BMS together in a 2nd life application could be facilitated. This topic gains much importance because, nearly in all EVs currently on the market, the BMS is placed inside the battery pack and completely sealed.

Within an EV, the communications between various ECU's, charger etc. happens using the CAN protocol defined by the standard ISO 11898. When it comes to vehicle to grid communication, it's the charger which communicates directly with the grid and not the BMS. Even though there are several standards like ISO 15118, IEC 61850 etc., which define vehicle to grid communication through the EV charger, they can't be applied in a stationary 2nd life application of an EV BMS, since an EV charger may not be present in a stationary application. There would be an energy management system instead which communicates with the BMS directly and a protocol should be defined for this communication purpose.

When it comes to stationary storage applications, they can serve a range of use cases like home storage, grid storage for production vs demand bridging, peak shaving etc. The nature of devices connected to the BMS and the connection architecture differs with the application nature, complexity as well as system provider. The most common possibilities are shown in Figure 6:



(a) BMS to EMU communication through inverter



(b) Direct BMS to EMU communication

Figure 6: Possible Architecture for BMS connection with 2nd life application components [61]

As seen from the figure above, when it comes to stationary storage applications, additional components like the inverter, energy management unit (EMU) etc. are included in the network. The inverter/power electronics takes care of bidirectional AC←→DC conversion while battery is in charging and discharging mode. The EMU is the subsystem which controls the operating mode of the battery pack depending upon the load conditions.

The inverters are generally provided with communication possibilities like RJ-45 or Ethernet or TCP-IP or RS-232 or CAN. The EV BMS already communicates through CAN, hence by choosing an inverter with CAN capability makes its integration with an EV BMS easier. But care should be taken regarding the differences in the configuration and the way of signal coding from device to device.

When it comes to direct communication between a BMS and an EMU, the BMS has a CAN bus, while the EMU may not have any possibility of CAN bus. The EMUs are generally operated through SCADA and communicate with other components in the network through TCP/IP connections.

Considering complete reuse of EV BMS, either Ethernet/TCP-IP ports could be included while designing the EV BMS or else a bridging communication device could be manufactured and provided when the EV battery pack is intended for 2nd life use case.

Even when coupling various electronic devices with a BMS through CAN communication, due to differences in signal coding, the CAN matrix of those devices is necessary for decoding and understanding the massages sent/received by them. But access to this CAN matrix is generally not allowed by neither the EV BMS manufacturer nor any other component manufacturer because confidentiality and security reasons.

Hence an additional filtering step should be included, which allows access to only the allowed required information while blocking the non-disclosable ones. Instead of displaying the CAN codes as they are, they should be transformed into different formats so that the receiver receives and understands only the required information. These features are currently not supported by the CAN protocol. Hence a higher-level public and open source protocol containing additional information about the data link, physical layer as well as the type of application/info/device sending or requesting info through CAN bus is recommended.

In addition to the CAN protocol used in EV BMS, the CANopen protocol should be included in the network for communicating with the EMU/inverter fulfilling the above-mentioned features/requirements.

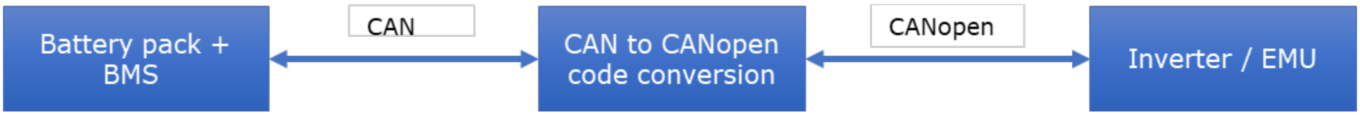


Figure 7: Bridging step between EV BMS and EMU/inverter

The CANopen protocol is also governed by the CiA301 standard which is a derivative of ISO 11898 which also standardises CAN protocol. The bridging step of CAN to CANopen code conversion should be standardised by involvement of EV BMS manufacturers and stationary application EMU manufacturers [61].

4.1.5 BMS second-life mode

This is a suggestive mode of operation for BMSs. Applicable standards for second-life application can play a role as a stakeholder, while working on requirements engineering of an application. This mode of operation could be called as second-life mode. Only an authorized maintenance personnel is allowed to change its mode of operation to second-life mode. The operational limits are adapted to the second-life application. And, depth of information shared via communication channel (for e.g. CAN) is limited and it is only relevant to the second-life application. A list of such relevant information is elaborated in Chapter 4.1.5.

4.1.6 Information to be shared by the BMS

As explained in the chapter above, battery packs could be used for 2nd life applications. The higher-level system would mostly change for its next life. For example, an EMU would require appropriate information about the battery pack and its state. The BMS can provide them. But the EMU would not require all the complex information and signals that an EV BMS would communicate. For controlling a stationary application, it would require limited set of information and signals.

The table below contains a list of most relevant parameters from an EV BMS that would be sufficient for an EMU. The data formats should be adopted from subchapter 3.4.4.

	Parameter	Treated purpose	Type
Pack Voltage	Momentous battery pack voltage	Instantaneous power calculations	Variable
	Maximum voltage of the battery pack	For charge power calculations	Variable
	Minimum voltage of the battery pack	For discharge power calculations	Variable
Battery pack current	Battery pack current	For safe operation of the battery pack	Variable
Cell voltage statistics	Mean cell voltage in the battery pack	For monitoring cell information	Variable
	Minimum cell voltage in the battery pack	For safety	Variable
	Maximum cell voltage in the battery pack	For safety	Variable
	Maximum cell voltage position in the battery pack	For locating difference in cell voltage distribution	Variable
	Minimum cell voltage position in the battery pack	For locating difference in cell voltage distribution	Variable

Cell temperature statistics	Mean cell temperature in the battery pack	Battery pack working conditions optimization, safety. Decision criterion for thermal management system.	Variable
	Minimum cell temperature in the battery pack	For safety	Variable
	Maximum cell temperature in the battery pack	For safety	Variable
	Maximum cell temperature position in the battery pack	For locating difference in cell temperature distribution	Variable
	Minimum cell temperature position in the battery pack	For locating difference in cell temperature distribution	Variable
Battery pack voltage limits	Minimum allowed battery pack voltage	For maximum discharge power estimations and deep-discharge protection	Constant
	Maximum allowed battery pack voltage	For maximum charge power estimations and over-charge protection	Constant
Battery pack cell Temperature limits	Minimum cell temperature allowed in the battery pack	For initiating the heating system in case of operation at lower temperatures, for safety and enhanced performance	Constant
	Maximum cell temperature allowed in the battery pack	For initiating the cooling system in case of operation at higher temperatures, for safety and long life	Constant
Battery pack current limits	Maximum allowed discharge current	For power and energy calculations	Variable
	Maximum allowed charge current	For power and energy calculations	Variable
Battery pack power limits	Maximum allowed discharge power	For power and energy calculations	Variable
	Maximum allowed charge power	For power and energy calculations	Variable
Initial capacity	Initial capacity of the battery pack	For energy, capacity fade and State of Health estimations	Constant
Current capacity	Available capacity of the battery pack	For energy, State of Charge, State of Health estimations	Variable
State of Charge	State of charge of the battery pack	For energy calculations	Variable
State of Health	State of health of the battery pack	For capacity update, energy and power estimations, and maintenance planning	Variable
Operating mode	Battery pack mode of operation	Read current mode of operation, request relevant mode of operation while operating e.g. Balancing, maintenance	Variable
Battery identifier	Battery Identification number	For Tracking battery pack over its lifetime	Constant

Table 6: Information exchanged between an EV BMS and its 2nd life application

5 BMS Standardization for an Application by Tailoring of relevant Functional Safety Norms

This chapter analyses the potential hazards that may arise from malfunctions of electrical or electronic components in battery powered applications. This study also deals with possible sources that would lead to such functional failures for which automotive safety integrity levels are assigned. This chapter only treats norms IEC 61508 and ISO 26262.

5.1.1 Functional Safety Requirements

Functional safety requirements are a set of qualitative requirements that were derived for generic battery systems defined for the purposes of this report. Additional research and analysis must be done to apply them to specific applications. The battery management system is intended to prevent and/or mitigate faults that can lead to hazardous scenarios. Malfunctions of components associated with battery system and their associated control systems also fall under these faults. A functional safety process is an analytical method that can be used to analyse the safety implications of a battery system design.

5.1.2 Analysis Steps

Functional safety analysis involves the following steps:

1. System definition: Initially the system boundaries within which the system is intended to operate are identified. Then the components and their interactions with the system and other components present within and outside the system are stated.
2. Hazard analysis: An application specific hazard analysis should be carried out to identify a list of possible hazards that may occur due to malfunction of components as well as their control functions.
3. ASIL assignment: The ISO 26262 risk assessment approach is applied to the identified hazards, and an ASIL rating is assigned to each hazard.
4. Generation of safety goals: A list of safety goals are defined in order to overcome the identified safety hazards as per their assigned ASIL ratings.
5. Safety analysis: This is performed on the relevant system components and interactions as defined in Step 1.
6. Functional safety: Concept and functional safety requirements are performed at the system and components level, based on research results and as per ISO 26262 guidelines [62].

5.1.3 General functions and possible malfunctions of a BMS

This section lists some of the general malfunctions related to BMS functionalities and corresponding potential hazards:

BMS Function	Malfunction	Potential hazard
Acceptance of energy from charging & regenerative braking	Excessive acceptance of regenerative energy or continuous acceptance of energy even after completion of full charge.	Overheating of cell occurs which may lead to venting or even thermal runaway.
Energy delivery	The energy demand is not fulfilled by the battery system.	Sudden loss of power delivery for the intended applications.
	Battery system delivers energy when there is no demand.	Due to voltage level imbalances, the components within the system may get

		exposed to high-voltage and risk of electric shock may occur.
High voltage contactors control	Does not connect when required.	No energy delivery to the connected load or demand.
	Unwanted HV contactors opening when there is energy demand.	Loss of power for application served and system primary functions.
	Unwanted HV contactors closing when there is no energy demand.	Due to voltage level imbalances, the components within the system may get exposed to high-voltage and risk of electric shock may occur.
	Loss of interlock signal control	Exposure to high voltage.
Thermal management control	Does not initiate thermal management system.	Cell overheating or thermal runaway.
	Commands under-cooling.	Cell overheating or thermal runaway.
	Commands under-heating.	Accelerated cell degradation or internal short due to lithium plating when operated/charged at very low temperatures.
State estimation	Does not estimate SoC accurately.	Overcharging and overheating of cell/violation of allowed operational limits.
	Does not estimate SoH accurately.	Insufficient knowledge about the cell life and capability to serve the intended application efficiently.
	Does not estimate SoP accurately.	Overcharging and overheating of cell/violation of allowed operational limits/under-utilization of battery pack capability.
Balancing	Does not balance uneven cells.	Incomplete charging/discharging of battery pack. Inconsistent aging between cells increases.
Pack monitoring	Inaccurate/ no current measurement	Cell overheating and thermal runaway in case of higher current flow.
	Inaccurate/ no voltage measurement	Exposure to high voltage, over-charge/discharge, no cell balancing.
	Inaccurate/ no temperature measurement	Cell overheating or thermal runaway. Accelerated cell degradation or internal short due to lithium plating when operated/charged at very low temperatures. Inaccurate estimation of temperature dependent parameters from model-based algorithms.
Communication and data transfer	Loss of sensor communication/corrupted measurement signal	Degradation or safety hazards due to violation of operation limits/Inaccurate estimation of SoC, SoP etc.
	Loss of communication/wrong communication	If HV contactors are not opened in case of crash, exposure to high-voltage or short circuit may occur.
Diagnostics	Incorrect / no diagnostics	Un-detected faults/failures leading to unintended component failure/under-performance/safety hazards.

Table 7: General functions and related malfunctions occurring on a BMS

5.1.4 Assignment of ASIL ratings to identified malfunctions

In this step of the hazardous analysis, an ASIL rating (A, B, C, and D, with D being the most severe. QM shall be addressed by quality management methods) is assigned to each identified potential hazard.

The ASIL rating is based on parameters:

- E: Exposure (frequency of occurrence of an event),
- S: Severity (extent of harm), and
- C: Controllability (ability to avoid or control any harm).

Since the ASIL ratings are specific to associated applications and operating needs, some generic malfunctions are selected for demonstration purpose.

Function	Malfunction	Exposure	E	Severity	S	Controllability	C	ASIL
Acceptance of energy from charging & regenerative braking	Cell Over- heating (Thermal Event)	System in private closed location. Probability of occurrence is very common irrespective of operating modes.	E4	Thermal event may extend beyond the system into the surroundings. Severe and life-threatening injuries (survival probable) are possible.	S2	This situation is normally controllable with fire alarms, and being a closed environment, threat to people will be less.	C2	B
		System in public open location. Probability of occurrence is very common irrespective of operating modes.	E4		S2	This situation cannot be controlled as people may not be aware and threat to life is high as it happens in an open environment	C3	C
Energy delivery/HV contactors control	Sudden loss/decrease of energy Loss of contactors control	Loss of speed in vehicle applications.	E4	Collision with other vehicles leading to life threatening injuries.	S3	Hard to control in most cases.	C3	D
		Limited or complete halt of load connected in case of stationary applications.	E4	Life threatening injuries only in case of safety critical applications.	S2	Situation can be handled in most cases.	C3	C

Table 8: Generic examples of functions and related ASIL ratings

Function	Malfunction	Exposure	E	Severity	S	Controllability	C	ASIL
Inaccurate current measurements	Overcharging/Cell Over- heating (Thermal Event)	System in private closed location. Probability of occurrence is very common irrespective of operating modes.	E4	Thermal event may extend beyond system into the surroundings. Severe and life-threatening injuries (survival probable) are possible	S2	This situation is normally controllable with fire alarms, and being a closed environment, threat to people will be less.	C2	B
		System in public open location. Probability of occurrence is very common irrespective of operating modes.	E4		S2	This situation cannot be controlled as people may not be aware and threat to life is high as it happens in an open environment	C3	C
Thermal management control	Cell Overheating (Thermal Event)	System in private closed location. Probability of occurrence is very common irrespective of operating modes.	E4	Thermal event may extend beyond the system into the surroundings. Severe and life-threatening injuries (survival probable) are Possible.	S2	This situation is normally controllable with fire alarms, and being a closed environment, threat to people will be less.	C2	B
		System in public open location. Probability of occurrence is very common irrespective of operating modes.	E4		S2	This situation cannot be controlled as people may not be aware and threat to life is high as it happens in an open environment	C3	C

Table 9: Generic examples of functions and related ASIL ratings

Function	Malfunction	Exposure	E	Severity	S	Controllability	C	ASIL
State of charge estimations	Over-charging/ Over-discharging/Overheating	System in private closed location. Probability of occurrence is very common irrespective of operating modes.	E4	Thermal event may extend beyond system into the surroundings. Severe and life-threatening injuries (survival probable) are possible	S2	This situation is normally controllable with fire alarms, and being a closed environment, threat to people will be less.	C3	C
		System in public open location. Probability of occurrence is very common irrespective of operating modes.	E2		S2	This situation cannot be controlled as people may not be aware and threat to life is high as it happens in an open environment	C3	A
Balancing	Uneven charging/discharging of cells in battery pack/over-charging (thermal event)/ accelerated aging	System in private closed location. Probability of occurrence is very common irrespective of operating modes.	E4	Thermal event may extend beyond system into the surroundings. Severe and life-threatening injuries (survival probable) are Possible.	S2	This situation is normally controllable with fire alarms, and being a closed environment, threat to people will be less.	C2	B
		System in public open location. Probability of occurrence is very common irrespective of operating modes.	E4		S2	This situation cannot be controlled as people may not be aware and threat to life is high as it happens in an open environment	C3	C

Table 10: Generic examples of functions and related ASIL ratings

Function	Malfunction	Exposure	E	Severity	S	Controllability	C	ASIL
Loss of insulation or short circuit	Electrical shock	System in private closed location. Probability of occurrence is very common irrespective of operating modes.	E4	Electric shock/ Thermal event may extend beyond system into the surroundings.	S2	This situation is normally controllable, and being a closed environment, threat to people will be less.	C3	C
		System in public open location. Probability of occurrence is very common irrespective of operating modes.	E4	Severe and life-threatening injuries (survival probable) are possible	S3	This situation cannot be controlled as people may not be aware and threat to life is high as it happens in an open environment	C3	D
Diagnostics/Communication	Delay in fault detection/loss of communication with components	System in private closed location. Probability of occurrence is very common irrespective of operating modes.	E4	Sudden failure of safety critical function leading to hazards.	S2	This situation might get hard to control depending upon the nature of fault.	C2	B
		System in public open location. Probability of occurrence is very common irrespective of operating modes.	E4	Thermal events may extend beyond system into the surroundings. Severe and life-threatening injuries (survival probable) are possible	S2	This situation cannot be controlled as people may not be aware and threat to life is high as it happens in an open environment	C3	C

Table 11: Generic examples of functions and related ASIL ratings [62]

CONCLUSIONS

The requirement for a standard for BMS functionalities and tests had been treated in this document. Considering the inputs from existing standards, BMS development (in WP6 at LION Smart) and summary from 'BMS standardization workshop' in the scope of Everlasting H2020 project, this report had been finalized. The document audits into existing standards for BMS and battery packs. It addresses the deficit in standards for a BMS development and validation. The functionalities of an adequately safe BMS, and various tests applicable in general are formulated.

Additionally, BMS development in focus of battery packs used in a second life application are also addressed. Furthermore, tailoring a BMS for automotive application has been discussed.

The standardization potential of the BMS had been successfully analysed. The outcome of this document will be a basic set of standards which will further be validated. Further goal could be the creation of a working group or a follow-up project that focuses on the development of concrete specifications which could serve as a basis for the development of international standards from establishments like IEC and ISO. The updates of this document will be publicized on the everlasting BMS standardization website. (https://everlasting-project.eu/bms-standardization/).

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