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AUTOMOTIVE ENGINEERING: SIMULATION AND VALIDATION METHODS

Alexander Thaler · Daniel Watzenig

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Foreword

Ongoing discussions about climate change and the related fuel economy challenges are moving the automotive industry more and more in the direction of pure electric driving. At this point, it is no longer a question of "if" electromobility will become reality, but rather a question of "when" it will become a reality, and which applications will be first to market. Worldwide legal reductions in carbon dioxide and emissions limits will essentially require the electrification of automobiles. In addition, there is an ongoing shift in consumer attitudes towards electric vehicles, which is evident in two examples: Tesla's electric Model S has already been very successful, and BMW plans to launch its electric i3 by the end of 2013. Those two models, which feature completely new vehicle technology that has been specifically developed for an electric powertrain, may already herald a new era of individual mobility.

One of the main factors driving this trend is that battery technology, which is at the heart of electromobility, has improved significantly in recent years. Particularly in the field of lithium-ion batteries, which are essential for plug-in vehicles (PHEV) and fully electrified vehicles (BEV) due to their high energy and power density, significant progress has been made in reducing costs and improving safety, performance and reliability. For example, energy density has been increased significantly, without compromising power capability. Today's 18650 lithium-ion cells, which are already in use in automotive applications, can achieve a capacity of more than 3Ah. Safety has also been increased significantly, such as via new separator technologies and/or improved chemistries (e.g. $LiFePO4$). Indeed, many measures have already been implemented in the battery management system to protect the battery from dangerous external events (e.g. overcharge, over-temperature, over-current).

However, from a consumer's perception point of view in automotive applications and over 20 years of experience in other commercial applications (e.g. mobile phones) have shown that there is still considerable room for improvement if drivers are to fully embrace electric driving and the related battery technology. Costs need to be further reduced, and the reliability, durability and safety of lithium-ion batteries can be enhanced. In terms of safety, for example, more must be learned about system safety and abuse tolerance under vehicle crash conditions. Such advances will require an even deeper understanding of the microscopic processes in batteries under both normal and abnormal conditions (e.g. misuse or crash situations). Furthermore, new analytical approaches must be developed to provide an enhanced insight into the electrochemical processes within the lithium-ion battery cells, which will in turn improve the accuracy of estimations of the remaining vehicle driving range by enabling a better state-of-charge determination of the cells.

This book contributes to this ongoing development effort by providing insight into the state of the art of lithium-ion battery technology modelling. It is designed to stimulate new ideas for the improved utilization of batteries in real application. From a long-term perspective, we hope that this book will help foster improvements of the technology itself and thereby help usher vehicle technology into the next era. While today's lithium-ion batteries are suitable for application in electric cars, it is clear that many improvements are still to come in terms of both the physics and chemistry of such batteries. Energy and power density, which directly affect driving range and vehicle performance, will be significantly increased; safety and reliability will be further improved; and the total cost of batteries will decrease once production figures reach automotive scale quantities. As a consequence, consumer acceptance will increase significantly, as vehicles driven by "horsepower" from combustion engines will become less attractive than quiet, environmentally friendly electric vehicles propelled by "kiloWatts". When this happens, PHEVs and BEVs will have truly arrived.

Graz, November 2013 Volker Hennige

Preface

During the last 10 years, the modern world has seen at least the second attempt to electrify the powertrains of road traffic vehicles. Beyond the battery, which is a key component in this electrification process, all other parts have been further developed. All power devices have made a huge step forward. The combination of powerful control devices and semiconductor enhancements are providing adequate functionality from a customer point of view.

Much research has been conducted on the electrochemical level, and there has been progress made on energy density and cost as well. However, currently there is no electrochemical energy storage system available that fulfils the energy demand of today's drive trains and the related passenger comfort functions. Of course, it is simple to blame the battery and argue that this technology does not cover the needs. On the other hand, we can see that society is embracing the need to be more efficient when using energy, a need which is particularly strong in the area of mobility. Thus, the trend towards the electrification of drive trains is revealing the essential weakness of today's vehicle concepts. In the past, the availability of fossil fuels, with their high energy density, fostered drive vehicle evolution. Due to the limitation of on-board installed energy in storage systems, public awareness of the low efficiency of current vehicles has been growing, and the automotive industry has grasped the demand for more efficiency.

Two developments are anticipated:

- An increase in efficiency on the drive-train level, comfort (HVAC, etc.) and safety functions within a vehicle
- An increase in energy density in terms of energy storage:
  - Energy density will increase on the chemical level
  - Technology integration aspects (e.g. ageing, safety) will become better understood and development processes will be implemented in the automotive industry.

This book provides a comprehensive overview of the current research work in the latter area (i.e. integration). The two main topics of this book, safety and ageing, both directly influence the size and utilization of the applied storage system.

Articles Related to Safety

In Chap. 1, Martin et al. offer an overview of today state-of-the-art safety standard. Although this standard is well defined in ISO 26262, from an overall system-safety perspective, important processes and methods are still missing. Since safety aspects influence cost, it is essential to understand how different safety measures reduce risk for a new product (e.g. a battery system) that is integrated into the vehicle environment.

In Chap. 2, Trattnig and Leitgeb provide an overview of the challenge of mechanical battery modelling in crash/crush battery simulations. The current challenge in this area is to bridge the gap between the battery's micro structures and the need to keep simulation effort manageable. The question is, how simple can a model be made while still preserving its ability to provide all of the necessary information at the vehicle level to enable crash-relevant optimizations.

In Chap. 3, Golubkov and Fuchs focus on the thermal runaway process. Their team is currently working to develop a basic, application-related understanding of this process. The knowledge of this process will enable the creation of a battery system simulation framework that can predict the propagation of thermal runaway within the whole battery and the vehicle as a whole.

Articles Related to Ageing

In Chap. 4, Pichler and Cifrain describe an approach for modelling the electrochemical battery cell with all of the necessary details. The major challenge here is to devise a model that covers the physical properties of the cell in nanometre scale (e.g. anode/cathode porosity) while still providing simulation output in a reasonable amount of time and with an acceptable level of quality. The final step is the optimization of the cell design and technology in front of the application (e.g. driving cycle), while also covering major ageing aspects. A detailed model of physical processes always requires real parameters derived directly from physical measurements. In Chap. 5, Weber et al. provide an overview of analytical methods for quantifying the ageing of lithium-ion batteries. Such laboratory work is a necessary input for the models mentioned above. Since a complex model uses parameters that are not directly measureable, in Chap. 6, Scharrer et al. present a mathematical method for parameter optimization. To demonstrate this method, they present the results of a synthetic fitting problem solved by a parallel-adaptive Markov chain Monte Carlo method.

In Chap. 7, Hametner and Jakubek present a data-based, chemistry-independent approach to nonlinear observer design for the state-of-charge (SoC) estimation. In order to operate the energy storage system throughout the required lifetime, knowledge of the SoC is essential, and one of the key factors related to ageing.

One significant challenge for all of these individual approaches towards improved safety and life time of battery systems is the complexity this component adds to the car. Standards in the automotive industry are particularly high, especially in terms of quality and durability, and all research conducted in these fields must be measured against these standards. In the field of applied research, the key to meeting these high standards is the combination of knowledge from different specialist domains.

Such collaboration can produce high quality, highly useful development environments (modelling, simulation tools, accompanying tests and standards). In this context, the coordination of the efforts of specialists from different industries and from research institutes is the way forward.

Graz, November 2013

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Contents

Chapter 1
Holistic Safety Considerations for Automotive Battery Systems

Helmut Martin, Andrea Leitner and Bernhard Winkler

Abstract The objective of system safety engineering is to develop a system with no unreasonable risk. To this end, risks caused by the electrical and/or electronic (E/E) system that could potentially harm persons must be analyzed, and appropriate risk reduction measures have to be considered in an early phase of development. This requires a close collaboration between different engineering disciplines in order to specify a comprehensive description of risk reduction and mitigation measures—the safety concept. The international functional safety standard ISO 26262 has to be considered for the development of E/E systems within road vehicles up to 3.5 tons. This standard focuses on E/E measures and considers other non-E/E measures only after the specification of the safety concept. In contrast, this chapter proposes a workflow for the elaboration of an integrated safety concept including safety measures from different engineering disciplines. Two main lessons learned were that the consideration of all kinds of risk reduction measures in the concept phase improves the understanding of the safety of the overall system, and involving various fields of expertise enables the development of a clear safety concept. This approach will improve the development of the overall system, while complying with the requirements of ISO 26262 for the development of E/E systems. The applicability of the introduced approach is demonstrated on an automotive battery case study, where the influence of various safety measures on the Automotive Safety Integrity Level (ASIL) determination has been taken into account in order to reduce the costs of E/E system development.

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1.1 Motivation

Hazardous voltage (HV) battery systems are a central part of battery-powered Electric Vehicles (EVs) or Hybrid Electric Vehicles (HEVs) [8], which are becoming more and more important. One reason is the high energy efficiency of E/E systems and the zero (local) environmental pollution of EVs. Their main disadvantage is the relatively short operation range, which is far less competitive compared to conventional vehicles with internal combustion engines. Conventional vehicles provide good performance and long operating ranges by utilizing the high energy-density advantages of petroleum fuels. HEVs combine the advantages of both technologies. Some of the main targets for batteries to be used in HEVs are low costs, high power density (e.g. 1,200 W/kg), very high cycle life time (e.g. 200,000 cycles of charge/discharge), long life time (e.g. 9 years), and safety. With the growing importance of e-mobility, automotive battery systems are becoming more important as well. High power (e.g. HEV up to 250 kW to provide more dynamic driving torques) and high energy application (e.g. EVs such as Nissan Leaf 36 kWh to allow longer driving distances) are already being applied in series-production vehicles. Increasing power and energy while decreasing the battery geometries leads to an increase of potential critical effects in the case of malfunctions.

This chapter focuses on safety aspects in the context of safety-critical automotive batteries for EVs or HEVs. Regarding functional safety (safety of the E/E system), the IEC 61508[1] [3] is the basic international functional safety standard applicable to all industries. The ISO 26262 [4] is an adaptation of this standard that is applicable to the development of safety-related electrical and/or electronic (E/E) systems in the automotive domain. One important aspect of functional safety is the potential risk of electronic malfunction, e.g. malfunction of the battery control unit caused by incorrect inputs or software errors. These malfunctions could lead to hazardous events for passengers, other traffic participants, and uninvolved parties (e.g. fire due to overcharge). The potential of malfunctions has to be lowered by gaining of possible faults, as well as their causes and effects, and by providing solutions for fault mitigation.

In particular, e-mobility is highly interdisciplinary, whereby risk reduction also results from different technical disciplines (e.g. mechanics, chemistry). This means that system safety has to consist of different safety disciplines as well (i.e. functional, electrical, mechanical, and chemical safety). One example for electrical safety could be the prevention of hazardous voltage through the use of galvanic disconnections or isolation. Mechanical safety aims to prevent the deformation of the battery in the case of an accident through the use of cell housings or the installation location for example. Chemical safety can prevent explosions or fire by using a mechanical venting outlet for toxic gases. All of these measures are applicable for the development of a safe system.

[1] IEC 61508—Functional safety of electrical/electronic/programmable electronic safety-related systems.

Functional safety covers one vital part of system safety engineering, but it is important to realize that other safety measures have to be considered as well. This chapter discusses some of the main issues regarding the safety of HV automotive battery systems on different levels of abstraction such as battery cell, battery module and battery pack.

This chapter is structured as follows: Sect. 1.2.1 starts with an introduction to the safety lifecycle following ISO 26262. Section 1.2.2 describes the technical background consisting of the basic architecture of a battery system, together with potential risks and risk mitigation on different levels of abstraction. To get a better understanding, these safety measures are classified in Sect. 1.3. Section 1.4 introduces a modified workflow, which is used to reduce the required Automotive Safety Integrity Level (ASIL) and thereby also the development costs of the electronic system through the definition of non-E/E measures. Section 1.5 concludes the work and provides an outlook on how the presented work will be continued.

1.2 Technical Background

This section introduces the topic of functional safety in the context of automotive systems. Furthermore, an overview of an HV battery system architecture is provided, including several basic safety measures from different engineering disciplines.

1.2.1 Introduction to Functional Safety Following ISO 26262

The ISO 26262 safety lifecycle encompasses the principal safety activities during the concept phase, product development, production, operation, service and decommissioning as illustrated in Fig. 1.1.

Figure 1.1 shows the safety lifecycle and highlights the concept phase and the relevant parts of the product development. The concept phase starts with the definition of the system (here called item), followed by a Hazard Analysis and Risk Assessment (HA&RA), in which all identified hazardous events are evaluated according to ISO 26262 specific risk assessment criteria (i.e. severity, exposure and controllability). Current hazard analysis techniques can be classified on a hierarchical structure of a system in bottom-up (e.g. FMEA) and top-down approaches (e.g. FTA). The most important, often-cited techniques for performing a hazard analysis are Preliminary Hazard Analysis [1, 6], Concept Failure Mode and Effects Analysis (Con-FMEA) [2], and Hazard and Operability study (HAZOP) [5]. By performing the hazard analysis we identified the following main hazards of the battery system: fire/explosion, toxic gases, hazardous voltage of the battery module/pack ($U > 60$VDC), leakage/venting of battery cells (corrosive/toxic (e.g. hydrofluoric acid)), fire (e.g. flammable materials) and explosion (e.g. breakdown of cell safety vent).

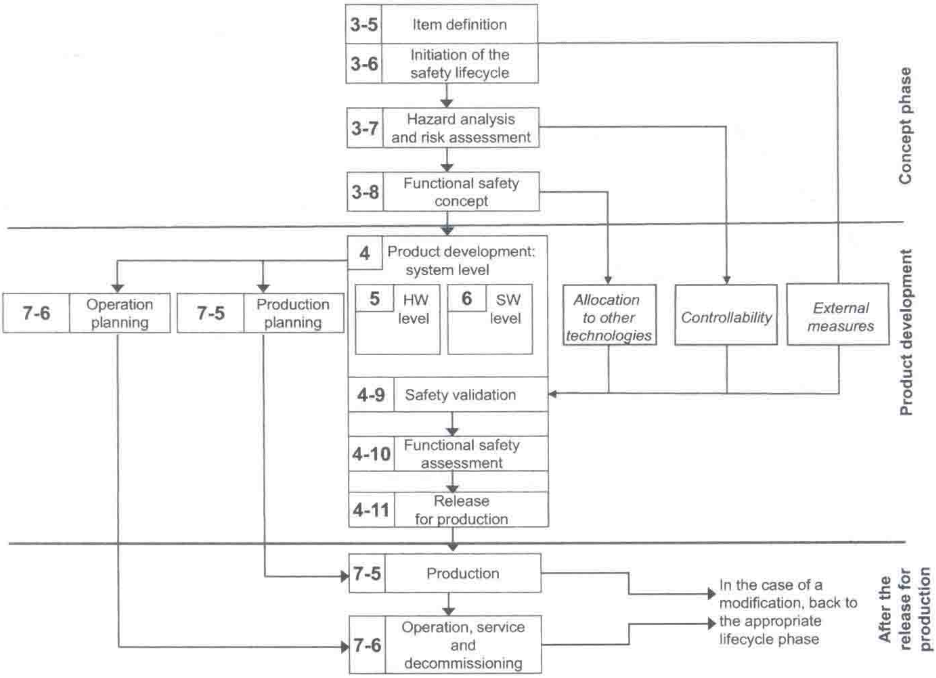

Fig. 1.1 Safety lifecycle according ISO 26262 [4]

The result of the risk assessment determines the ASIL, which indicates the risk of occurrence of a specific failure mode[2] and its necessary degree of avoidance. ASIL values range from ASIL A (low criticality) to ASIL D (high criticality).[3] Depending on the derived ASIL, the ISO 26262 recommends methods for fulfilling the requirements—higher ASIL leads to higher efforts and costs during the product development.

Based on the results of the HA&RA, safety goals[4] are defined for each hazardous event, and the corresponding ASIL is allocated to each of them. The final activity of the concept phase is the elaboration of the Functional Safety Concept, which defines safety measures that must be fulfilled by the design and development of the system to avoid an unreasonable residual risk. Safety measures are activities or technical solutions used to avoid, control or mitigate the harmful effects of systematic failures and random hardware failures. These technical solutions are implemented by (i) E/E measures (e.g. E/E system with sensor → controller → actuator), (ii) external measures (e.g. organizational measures to counter technical flaws) or (iii) other technologies (solutions from other technical domains, e.g. mechanical

[2] *"failure mode = manner in which an element or an item fails"*. [4]

[3] The class QM (quality management) denotes no requirement to comply with ISO 26262.

[4] Safety goals represent top level safety requirements.

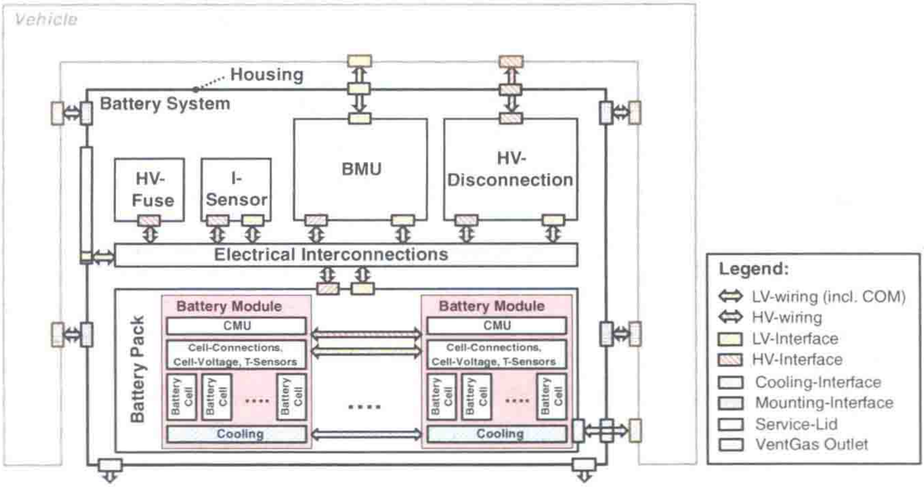

Fig. 1.2 Battery system architecture—Illustration of the main parts of an automotive battery and their interrelations

fault-back solution), which detect faults or control failure modes in order to achieve or maintain a safe state.[5]

1.2.2 Description of Automotive Battery System Architecture

Figure 1.2 shows a schematic representation of a system architecture of an HV lithium-ion battery. It consists of the following main components, which already include or represent basic safety measures:

- **Battery Management Unit (BMU):** The main functions of the BMU are the electrical and thermal management, diagnosis functions, insulation monitoring, and the communication with other parts of the vehicle. Electrical management includes charge balancing, charge determination, and the provision of status information, such as system voltage, system current, or power-time prediction (charging/discharging) for vehicle control functions. Thermal management functionality is used to monitor and evaluate the temperature in the battery system. Disconnection monitoring, charge monitoring, and fault recording represent different diagnosis functions. The insulation monitoring in the battery system is a coordinated function between the battery system and the vehicle.
- **HV Disconnection:** Its main purpose is the disconnection of the battery system from the vehicle HV circuit, and it provides a galvanic separation of the battery and the vehicle in case of deactivation, accident or a safety-critical malfunction. The HV disconnection consists of special HV contactors for the plus and minus

[5] *"safe state = operating mode of an item without an unreasonable level of risk of the system"*. [4]