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Accelerated Development and Test of BMS using an Emulation-based HIL

Christoph Kettenring[1], Michael Schwalm, Tatjana Dabrowski, Mathias Thiele, Matthias Puchta
[1]*Christoph Kettenring (corresponding author)*
Fraunhofer Institute for Wind energy and Energy System Technology, Königstor 59, 34119 Kassel, Germany
christoph.kettenring@iwes.fraunhofer.de

Abstract

Battery management systems are a mandatory instrument in the regulation and control of electrochemical energy storage. The test and validation of state detection algorithms and thermal and electrical management are challenging issues in the development of these systems. Emulation-based hardware-in-the-loop test setups provide the required reproducible and reliable reference values of the battery systems as well as high current capabilities and high voltage-dynamics. Moreover, they can be performed in a cost and time efficient way.
Keywords: lithium-ion battery, state of charge, state of health, battery management system, hardware-in-the-loop

1 Introduction

The implementation of electro-mobility and the necessity to compensate the feed-in of volatile renewable energy sources into the grid have increased the importance of electrochemical storage systems such as lithium-ion batteries. To satisfy the demands on the specific operating conditions for electrically interconnected and thermally interacting lithium-ion cells an appropriate management system is required that ensures an efficient and safe operation. Crucial functions of a Battery Management System (BMS) are homogenization of the various states of the cells via appropriate algorithms as well as the state detection of each individual cell in the compound of the battery system. Both the development and the testing of BMS via a test setup with a great number of lithium-ion cells and their complex preconditioning are time-consuming and cost-intensive. Apart from the safety requirements, the repeatability and validation of cell states, in particular regarding the State-Of-Charge (SOC) and the State-Of-Health (SOH) with a reliable reference value, are further challenges of the BMS [2].

For the complex test setups the use of appropriate Hardware-In-the-Loop (HIL) environments is particularly suitable. In so doing, the various cell states such as SOC, SOH, and temperature can be set in a fast, entirely reproducible and fully automated way. Moreover, the usual safety precautions regarding the handling of physical lithium-ion cells can be omitted. Another great advantage is the use of Newman models for the HIL control. These models are based on the complex electrochemical and physical processes within the cells. While in experiments solely electric current I, voltage U and temperature T are available, such test setup software also provides insights into the internal quantities and processes of a battery cell. This allows precise monitoring of the state during development and testing and the immediate validation of the state detection algorithms of the respective BMS.

To handle the high dynamical compensating currents of an active BMS, appropriate voltage sources and sinks are required by the HIL test setup. Real-time capable software based on Newman models simulates the battery behavior with a high accuracy over the entire operating range. The combination of a real-time simulation of each lithium-ion cell and the precise emulation of thermal and terminal behavior enables to support the development and testing of BMS.

2 HIL environment

The requirements of the HIL environment are the availability of a correspondingly high number of channels for the terminal and thermal sensor emulation as well as the emulation of the current sensor of the entire battery pack. The power supply units for the terminal emulation have to emulate the battery cells within their voltage and current ranges according to cell chemistry and design. These are the preconditions to emulate the behavior of an entire battery pack.

However, depending on the design, BMS provide a variety of other I/O-ports and -interfaces for control and communication purposes. For a complete verification of a BMS these have to be provided by the HIL environment as well. The emulation of additional battery system components, such as cooling and heating systems, is necessary to control the various interfaces. In addition, further circuits are required to generate failure scenarios and to perform current measurements of each individual emulated cell. In order to measure the compensating currents of an active BMS exactly, high-precision current measurements with sampling rates of less or equal 0.1 ms are required. Only the complex interplay of all components of the HIL environment allows the emulation of all possible nominal operating conditions and relevant failure scenarios in a realistic manner.

Current active balancing circuits as well as BMS slaves for monitoring the cell states use cycles of 1 ms and less. Thus, high dynamics and accuracy of the emulation outputs are mandatory. The electrical properties of cell emulation channels in a source and sink operation mode are given in Table1.

Not only the emulation of cell behavior, but also the simultaneous calculation of the multitude of applied models with the required temporal resolution during the test duration is fundamental for an accurate emulation of the environment of a BMS.

Table 1: Electrical properties of cell emulation channels.

Parameter	Range
output voltage	1 - 6 V
output current	0 2.5 A
output power	0 - 15 W
DC-ripple, peak-peak	$<$ 2.5 mV
DC-ripple, effective	$<$ 10 mV
maximum overshoot	$<$ 10 mV
build-up time	$<$ 20 ms

3 Lithium-ion battery model

Simulations and HIL tests play an important role in the development process of BMS since they enable great time and cost savings. The applied model based on Newman's approach to electrochemical energy storage is briefly introduced in the following.

3.1 Modeling approach

Basically, there are three different macroscopic approaches to battery modeling. We distinguish between black-box, gray-box, and white-box models. In the case of black-box models virtually no knowledge about the system to be modeled is required. The structure as well as the parameters of these models are obtained by extensive measurements in the laboratory. These models include for example neural networks. In this approach, the user is not given any insight into the processes during the simulation. A significant advantage is, however, that such models usually require only a low computing power.
In the case of gray-box models, typically in form of an electrical equivalent circuit, part of the parameters provides a physical meaning. In this modeling approach, except for the input and output characteristics of a battery cell, internal quantities can be considered only in a limited extent. This approach has also only a low computational cost. However, it displays the highly non-linear battery behavior solely in a certain operating point (SOH, SOC, I, T) and not over the entire operating range. This approach is frequently used due to its simple implementation, partially also extended by family of characteristics for parameter tracking, however, has considerable disadvantages regarding the accuracy.
The multi-physical description (mass transport, charge transport and reaction kinetics) of the white-box model results from an exact theoretical description of the actual electrochemical and physical processes. All model parameters possess a physical meaning, thus, insights into the cells during runtime are possible. For the development of a white-box model a deep understanding of the system is required. This approach is typically more computation-intensive than the previous approaches, but reproduces the non-linear battery behavior over the entire operating range. The white-box model applied here is based on the category of Newman models.

3.2 Battery pack

In battery packs individual cells are interconnected both electrically and thermally. In principle, the electrical interconnections can be arbitrary combinations of serial and parallel connections. In order to model the thermal interaction in the battery pack, spacing between the individual cells, specific heat capacities, and heat conductivities of the filling material or the filling gas have to be considered. It must also be taken into account that each individual cell can take an arbitrary position in the pack and can display production tolerances. Furthermore, the respective aging of the individual cells usually differs.

3.3 ISET-LIB Software

The ISET-LIB software developed at the Fraunhofer Institute for Wind energy and Energy System technology (IWES) is based on the white-box modeling approach and belongs to the class of the Newman models [3]. The software simulates the behavior of lithium-ion batteries under various operating conditions assuming a model of all relevant physico-electrochemical processes. Constructive data as well as characteristic parameters of the cell chemistry serve as input parameters, whereby virtually any desired form can be simulated without having to carry out complex series of measurements for the parametrization. As a result, different aged states can be modeled as long as the corresponding physico-electrochemical changes are known. Regardless of this, the approach provides a detailed view into the internal processes of lithium-ion cells, which greatly benefits the development of new concepts and BMS. By this means, state detection algorithms can be effectively tested and enhanced since the (model) state of the simulated cell is known at any time.
An example of the internal quantities provided by ISET-LIB are shown in Fig.1. The software emulates

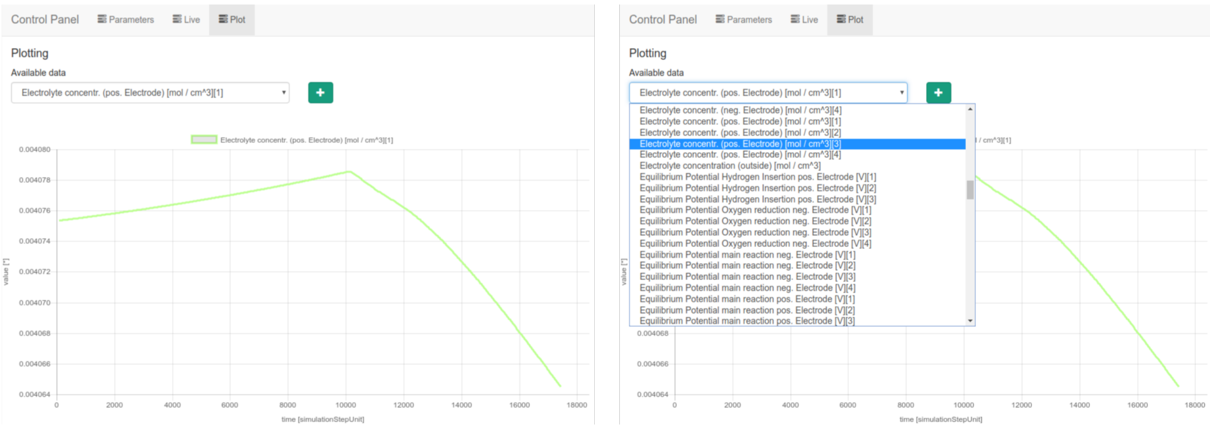

Figure 1: Internal quantities provided by ISET-LIB.

the highly non-linear behavior of a cell so that a high simulation accuracy can be obtained over the entire operating range. In addition to the initial state, the temperature as well as a current or a voltage profile at the terminals serve as input parameters. Moreover, the connection of several cells to a pack with corresponding thermal and electrical interactions is possible.
Features at a glance:

- non-linear model
- prediction of the terminal behavior
- high accuracy over the entire operating range
- simulation of arbitrary states
- insights into internal processes
- accurate knowledge of all states

- parametrization via constructive data
- emulation of arbitrary aged states
- real-time version for HIL test setups

The real-time version of ISET-LIB, which is implemented on a network of real-time computers, is combined with high-precision and dynamic voltage sources to emulate the battery pack precisely.

4 Emulation-based HIL test setup

The analysis of active compensating algorithms and compensating circuits is a crucial part in the development of BMS. Emulation-based HIL environments accelerate the development and testing of BMS due to the possibility to change the initial state of each individual cell in a fast, precise and absolutely reproducible way via the test setup software. Safety issues are completely avoided by the use of intrinsically safe power supplies. In contrast to physical cells, an emulation-based test setup additionally provides all internal quantities, so that precise monitoring of the individual cell states of the emulated pack is possible during the development of BMS and its corresponding algorithms. A draft of the emulation-based HIL test setup is shown in Fig.2.

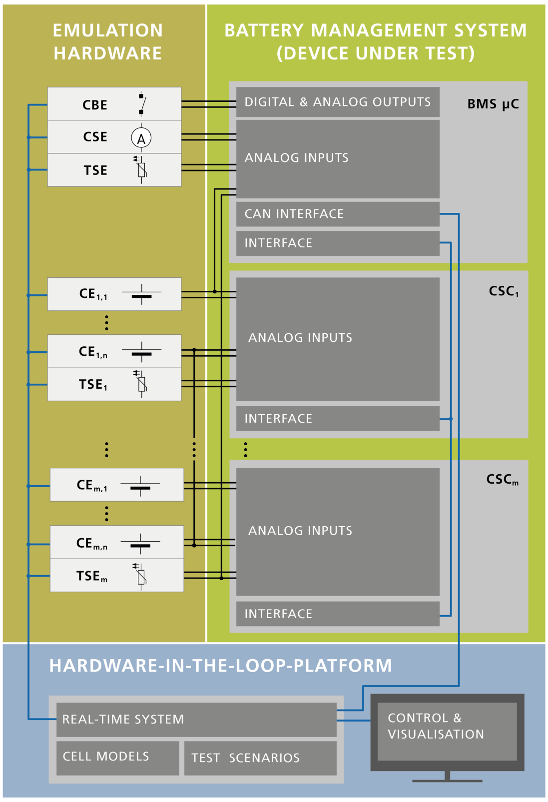

Figure 2: Emulation-based HIL test setup.

Advantages of the HIL concept are the safety aspects, a rapid change of the operating points as well as the absolutely reproducible test procedures with an accurate knowledge of the cell conditions. The provision of cell-internal reference values is mandatory for the future development of algorithms for state detection.

Summary of requirements:

- potential separation between the emulation channels
- output voltage and current range according to the desired cell chemistry and design as well as the desired failure scenarios such as line break, undervoltage, overvoltage, etc.
- limitation of the output current for tests on active compensating algorithms and short circuit tests
- high current and voltage dynamics and accuracy
- simultaneous calculation of the cells with the required accuracy and temporal resolution
- simple parametrization of the cells and test scenarios
- visualization and recording of the tests carried out

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Authors

Graduate industrial engineer **Christoph Kettenring** studied industrial engineering at the Technical University of Kaiserslautern and at the University of Kassel. Since 2014 he is working as a research assistant in the department for energy storage at the Fraunhofer Institute for Wind energy and Energy Systems in Kassel. Currently, he is researching and developing real-time systems for single-cell and battery pack emulation.

Dr. **Michael Schwalm** studied physics at the Philipps-University of Marburg with a focus on experimental semiconductor physics. He graduated in 2011 from his subsequent dissertation on methods for investigating and improving novel solar cells. Since 2011 he is working as a research assistant in the department for energy storage at the Fraunhofer Institute for Wind energy and Energy Systems in Kassel. He is responsible for the parametrization of lithium-ion and lead-acid batteries and the mathematical modeling of electrochemical processes. Currently, he is working on aging phenomena in lithium-ion cells and the mathematical modeling of aged batteries.

Dr. **Tatjana Dabrowski** studied physics and mathematics at the Georg-August-University of Göttingen with a focus on theoretical solid-state physics and numerical mathematics and optimization. She graduated in 2015 at the University of Bremen from her subsequent dissertation on the theoretical investigation and simulation of lithium/air batteries. Since 2016 she is working as a research assistant in the department for energy storage systems at the Fraunhofer Institute for Wind energy and Energy Systems in Kassel. Currently, she is working on the modeling of lithium-ion and post-lithium batteries as well as the mathematical modeling of aging phenomena.

Mathias Thiele studies computer science at the University of Kassel. Since 2015 he is working as a student assistant at the Fraunhofer Institute for Wind energy and Energy Systems in Kassel. Currently, he is working on battery pack emulation and the graphical user interface for the simulation of electrochemical energy storage.

Graduate engineer **Matthias Puchta** studied electrical engineering at the University of Kassel. He is heading the department for energy storage systems at the Fraunhofer Institute for Wind energy and Energy Systems in Kassel. His activities include the technical and organizational management of the department and the realization of R&D energy storage projects for industrial customers and public entities in the fields of electrochemical energy storage as well as compressed air, offshore pump storage and power-to-gas. He is a member of the Fraunhofer Battery Alliance which focuses on state-of-the-art and novel electrochemical energy storage technologies.