Efficient Modelling of Heterogeneous Battery Management Systems

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Abstract. A simulation environment for the design of battery management systems (BMS) based on the modelling languages SystemC/SystemC AMS will be presented. Models of battery cells, the temperature and current sensors, the components for balancing of the battery cells, the integrated circuits to monitor the cell voltages and the interface for the data transmission to the controller where the BMS software is running describe the hardware. The software can be integrated via an AUTOSAR RTE compliant application programming interface into the simulation. The approach allows considering the nominal as well as the faulty behaviour of components. The simulation environment is integrated into the design environment COSIDE.

1 Introduction

The relatively low energy density of available electrical energy storage elements and their limitations for automotive applications currently form the critical point in the area of electro mobility. Therefore, the best use of battery cells regarding their capacity to extend the range of electric vehicles (EVs), increase of the life span of cells to decrease the costs of ownership, and the safe operation of battery cells are required. An optimal and intelligent battery management is essential to achieve these objectives.

The BMS must ensure the optimal charging and discharging of the battery over its lifetime and make sure that the battery never reached a critical state, which can lead to their destruction, fires or explosions.

Within the project IKEBA [1], a prototype of a virtual design platform is implemented, which allows to check the suitability and the interaction of selected hardware components (lithium-ion batteries and semiconductor circuits to monitor the battery status) and the software of a battery management system (BM software) by means of simulation. This way, the development of battery management systems including their software is supported. Investigations on how to increase the range of electric vehicles for different driving conditions by improvements of the battery management software and the characteristics of the applied hardware can be carried out using the design platform.

Partners in the project IKEBA are the Hella KGaA Hueck & Co, the Atmel Automotive GmbH, the Institute for Applied Materials - Applied Material Physics of the Karlsruhe Institute of Technology and the Fraunhofer-Gesellschaft e.V.

2 Implementation

The design environment COSIDE [2] for the development of electronic systems is the basis for the virtual simulation platform. COSIDE is a tool that allows handling of high complex electronic or heterogeneous systems together with the software that runs on these systems. Such systems can be modelled and simulated within COSIDE.

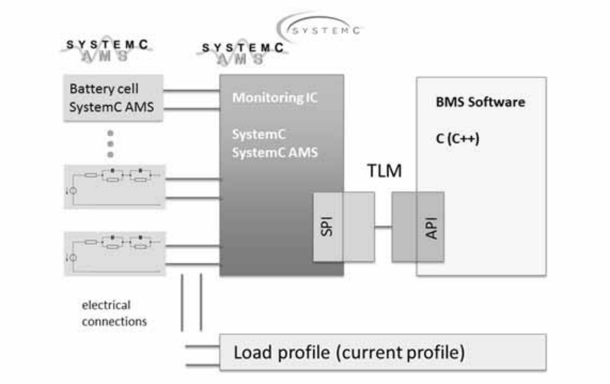

Figure 1: Components of the BMS Design environment.

The model creation for the hardware components is done with the SystemC and SystemC AMS hardware description languages. This approach allows a detailed inclusion of the components of the battery management integrated circuits (BM ICs) considering the characteristics of the Analog-to-digital converters (ADCs), delay times of the digital components, and the data interface (specifically SPI, the Serial Peripheral Interface) between BM ICs and battery management controller. The properties of batteries, circuits to compensate unequal state of charge of cells (cell balancing) and different load profiles can also be described. SystemC/SystemC AMS allows a compilation of the model descriptions for a fast simulation. For the development of the BM software an AUTOSAR RTE (Real Time Environment) provides a compliant application programming interface (API) with the required C function interfaces.

The virtual design platform is tested using a hardware demonstrator in the IKEBA project. The expected nominal behaviour is simulated and can later be compared with measurement results in order to validate the approach that is used for the virtual design platform. Later on, different concepts to operate the battery cells can be compared by means of simulation with the aim of increasing the range of an EV.

A number of models using SystemC and SystemC AMS have been created in connection with the modelling and simulation of the hardware demonstrator. A parameterization was done for the components that are to be used in the hardware demonstrator. Table 1 gives an overview of the currently existing models that have been implemented at Fraunhofer IIS/EAS. Through exchange and extension of models, the described solution can be easily adapted to other applications.

	Model	Description
Battery	battery_cell	Table model for battery cell
	cell_temp	Heat generation in the battery cell and exchange with the environment
	battery_pack_6s1p	Battery stack (6 battery cells in series)
BM IC	bmic_eln	Model of the electrical terminal behaviour of the BM IC for measuring and monitoring battery stacks in hybrid and electric vehicles
BM IC	bmic_simple	Behavioural model for BM IC for measuring and monitoring battery stacks in hybrid and electric vehicles.
Environment	simple_hvcs_eln	High voltage current sensor
	ntc_thermistor_characteristic	NTC resistance characteristic with temperature dependency
	temperature_measurement_eln	Resistance circuit for temperature measurement
	file_in_eln_isource	Source with reading a current profile from a file
BM Controller	RTE	AUTOSAR RTE compliant API of the BM controller (BM-software)
TLM	tlm2spi_target	Transaction Level Model (TLM) interface for SPI (for connection of the BM the BM IC controller)
	tlm_current_sensor	TLM interface for Local Interconnect Network (LIN) modelling (for connection of the power sensor to the BM controller)
	tlm_controller	TLM model of the BM controller

Table 1: Models for virtual design platform.

3 Example

The following Figure 2 shows the schematic and the corresponding non-electrical parts for a BMS system model, which was developed in the IKEBA project.

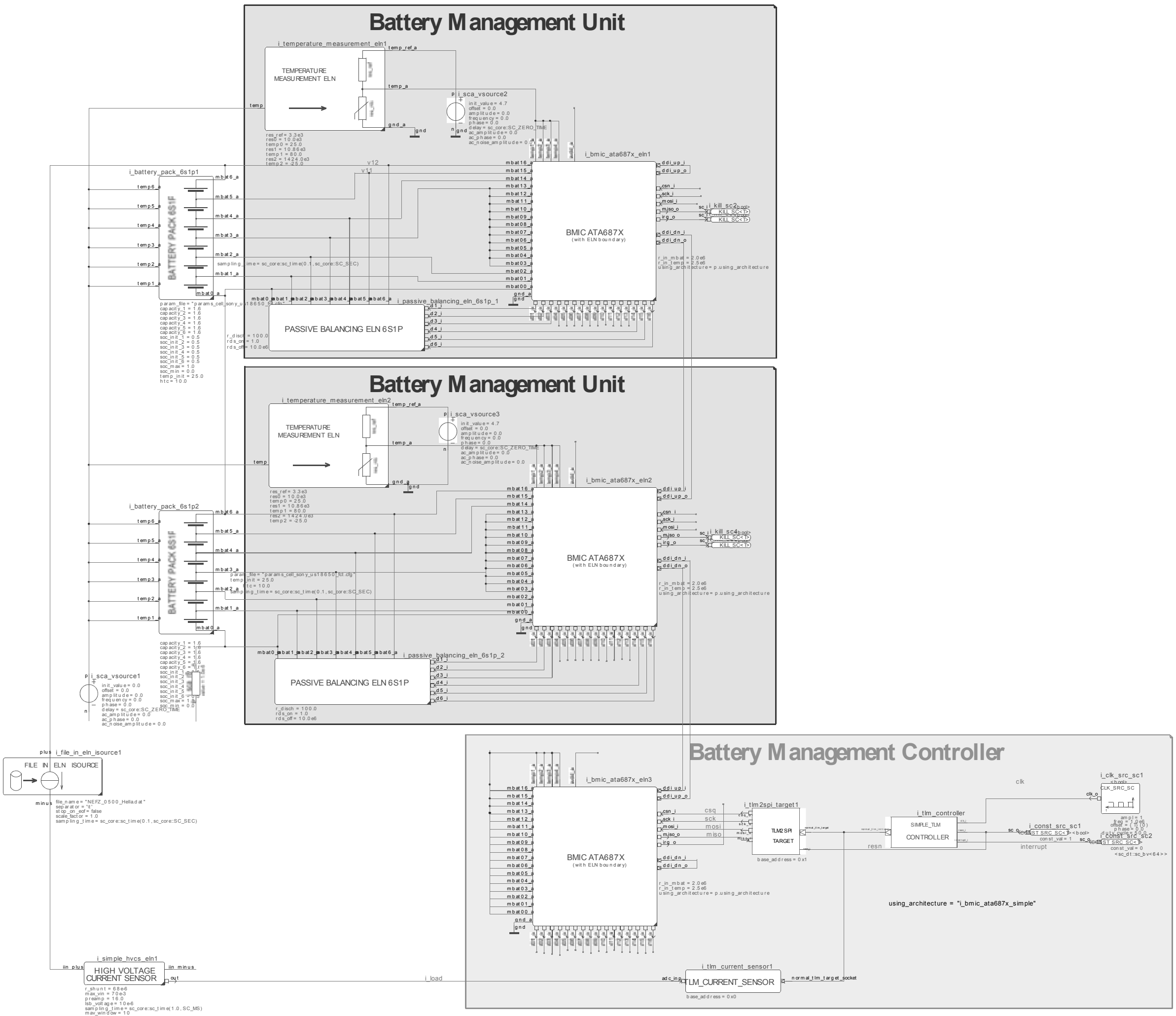

Figure 2: Top level description of a BM system model.

A generic approach, whereby individual components can be exchanged was applied here. A possible application is the investigation of the accuracy requirements of the ADCs for the voltage, current and temperature measurements. The function of the BM software regarding exchange of individual components such as battery cells and monitoring ICs can be checked. For investigations at system level a high performance of the simulation is mandatory to get meaningful results within a reasonable time. To ensure this, efficient modelling approaches as an abstraction of the data bus interfaces at the transaction level (TLM) are applied.

At this level, the focus is less on the physical implementation of the interface, the real signal realization, but more on the transaction of data itself. This supports a generic modelling approach, where changes of the implementation of the bus system can easily be realized. This concerns the connection to additional components or the use of system components from other manufacturers. In conventional modelling approaches, modifications of the interface specifications require to change also the connected models. This would not be a generic approach. In automotive electronics, a variety of different interfaces for the connection of controllers with each other or to other circuits in the system is applied. In addition there are mostly misused variations of these interfaces. However, the exact connection of bus components and their modelling at low level plays usually only a minor role for functional system investigations. Furthermore, the TLM method improves the simulation performance and offers high efficiency, since the low level signal behaviour must not be reflected by the models. A high efficiency is also a prerequisite to perform statistical analyses or parameter variations.

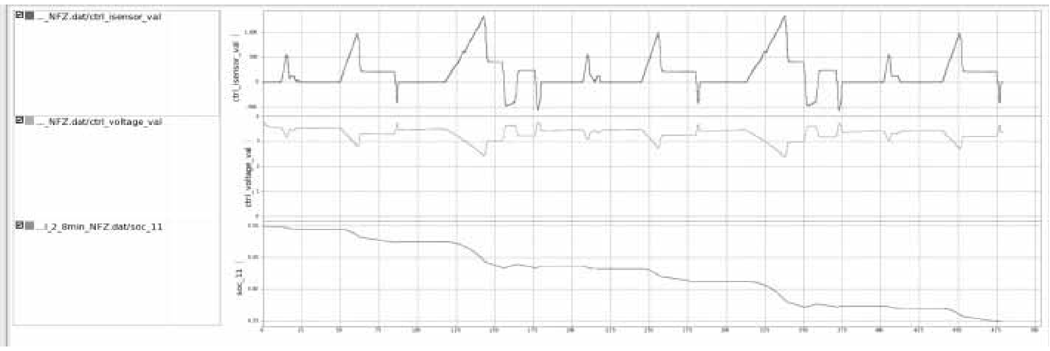

Figure 3: Current profile, voltage and SOC of a battery cell.

An example is given by the connection of the BM ICs with the battery controller and the inclusion of the BM software in the system description. Figure 3 shows simulation results for the battery voltage and SOC history based on a predefined current profile that corresponds to a NEFZ drive cycle for a special car.

4 Selected Models

4.1 Model for the battery cell

The batteries are composed of lithium-ion cells. The model of a single cell is described in SystemC AMS. The network model consists of an open circuit voltage V_{oc}, an internal resistance R_{IN} in series with two RC circuits R1 || C1 and R2 || C2, see Figure 4:

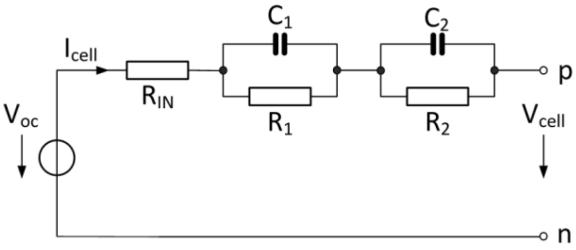

Figure 4: Structure of a cell model.

R_{IN} mainly represents the static internal resistance, the RC circuit R_1 || C_1 models the regeneration after loading and unloading with a time constant of about a minute and the RC element R_2 || C_2 contributes to the AC impedance with a time constant of about 1 ms. The elements of the equivalent circuit depend on the state of charge (SOC) of the battery cell and its temperature. The state of charge is updated w.r.t. the charge and discharge currents of the cell and the cell capacity that depends on the temperature.

The dependencies of the elements of the cell model can be determined based on measurement results for the loading and unloading of selected cells using the current interruption technique (CIT) [3]. For selected values of SOC and temperature, the corresponding parameters of the equivalent circuit model are determined. The dependencies are provided in the cell model by interpolation between table data points. Because the changes in SOC and temperature are "slowly", the model uses at the actual simulation time point their values at the last accepted time point. Thus, the evaluation of the battery model is a linear problem at each simulation time point. This circumstance helps to speed up the simulation. Analytical models to describe the dependencies require knowledge of cell parameters and make assumptions of functions that describe SOC and temperature dependencies. A widely used approach is suggested by Gao et al. [4] and also implemented in the design environment.

4.2 Interfaces of BM IC and BM controller

The interfaces of BM ICs and flow meter to the battery management controller have been described with transaction-level models (TLM). The following functions are supported by the transaction-level models:

- Initialization BM ICs
- Initialization of the high voltage current sensor
- Making available cell voltages using the BM ICs. If necessary separate functions for
  - Start the measurements
  - Read the values
- Making available cell temperatures using the BM ICs. If necessary separate functions for
  - Start the measurements
  - Read the values

- Making available currents through cells in series using the high voltage current sensor. If necessary separate functions for
  - Start the measurements
  - Read the values
- Control BM ICs signals for cell balancing

4.3 BMS application software interface

The BMS application software can access values provided by the BM ICs and the current sensor using compliant application programming interface (API) corresponding to an AUTOSAR RTE.

4.4 Inclusion of the BM - software

In order to include the battery management software in the system simulation, a controller model must exist which interacts with the hardware components. This is implemented by a generic model of the controller that calls the software applications with the help of a scheduler process. The scheduler process is sensitive to the external clock, reset and interrupt signals.

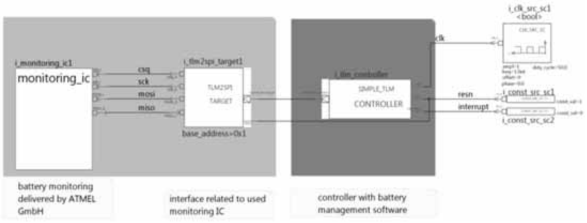

Figure 5: Interface with BM IC and BM controller.

Furthermore, access functions on the so-called hardware abstraction level are provided. These functions can be used by the software components. When calling such a function by a software application, a corresponding TLM transaction is initiated by the controller model. The transaction realizes the access to peripheral hardware. This approach provides an opportunity for high-performance access to hardware components. The access is independent of the actual physical interface. As another advantage, the software can be used for different architectures and peripheral configurations. It is only required that the selected hardware address is valid.

Thus, this solution enables a clear separation of the individual components. They can be developed consistently.

If the target hardware model has no TLM - interface, a conversion between the TLM representation and the real-world interface signals must be carried out. This was necessary for the BM IC model. For future applications, the converter model could be generated automatically based on the underlying fundamental basic libraries (e.g. TLM Sockets) and the specification of components (e.g. SPI frames for specific ICs).

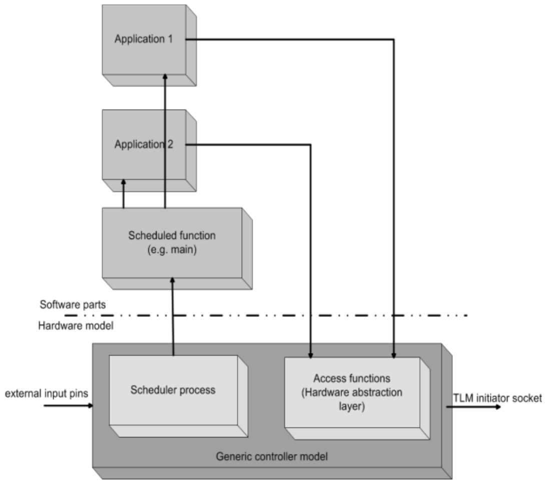

Figure 6: Generic controller model and implementation of software applications.

4.5 Hardware-in-the-loop application (HiL)

The system model can also be used for HiL (Hardware-In-the-loop) simulations. The SystemC/SystemC AMS [5] models are provided at a high abstraction level. This ensures a high simulation performance with sufficient accuracy, which is a prerequisite for modelling the real time use on a HiL system. While individual modules of the system are replaced by real, existing hardware components, other modules remain virtually. Potential benefit of this separation is the reduction of the simulation and model development time. Existing hardware components can be used together with models that run on a special HiL hardware. The models running on the HiL hardware emulate the corresponding components. Thus for instance, models can be used for components that are under development. This approach can also be applied to avoid problems with components that could be destroyed in the test process or that are dangerous or expensive.

A meaningful separation of real and virtual components of the system introduced in section 3 is to realize the battery, the BM IC behaviour, and current and temperature sensors using HiL hardware. The HiL hardware components are connected with the real BM controller. The BM software is running on the real BM controller.

The decision, to simulate the battery, is based on following basic benefits. A battery contains complex chemical and physical processes which are not reproducible and need time to adjust. SOC and temperature conditions can be modified in an easy way. There are high safety standards that must be fulfilled if a real battery is used for test purposes. Thus, real battery hardware should only be used in an advanced stage of development of the BMS. In the case of HiL simulations this is without meaning. Also the failure behaviour within the battery pack such as cable breaks, short circuits or intermittent contact can be realized easily within the HiL simulation. It is also possible to apply a number of drive cycles in the test procedure. Furthermore, the requirements for the components of the BM IC can be checked with a huge number of HiL simulation runs.

5 Outlook and Summary

The quality of a system also depends on the ability to react on incorrect or unexpected conditions. A system must be able to respond as expected and be robust to disturbances. Simulation allows investigating the system behaviour with faulty component behaviour. A library for the fault injection is prepared within the design framework. It contains generic structures to be able to reproduce incorrect behaviour in a simple manner. It is a special advantage of the approach that error descriptions are not part of the design under test (DUT). Error structures can be injected by the design environment to existing test benches without changing the test bench descriptions. This achieves a clear separation between system models and test environment.

Furthermore, the robustness of the system against parameter tolerances can be investigated using statistical analysis methods. The model descriptions based on SystemC AMS enable high simulation efficiency at system level. Libraries and experiences from other projects can be re-used for these tasks [6].

Simulation is an essential part of the development of complex heterogeneous battery management systems. It should support the investigation of the interaction of the battery, sensors, battery monitoring ICs, battery management controller and the application software. Compared to previous activities in this area, we developed an approach that allows considering all these parts in a simulation environment. It also supports the specification for specific hardware components as BM ICs. Consequences of hardware failures can be investigated in the test process in an easy way. The model development is based on SystemC/SystemC AMS. This approach opens the door to HiL hardware applications with models of the battery and electrical components straight forward.

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