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Low-temperature charging of lithium-ion cells Part II: Model reduction and application

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HIGHLIGHTS

- Model reduction of an electrochemical model.
- New identification-based model reduction process.
- On-board applicable, linear parameter-varying model as a result of model reduction.
- Application of the reduced model in charging control.
- Reduction of charging duration for low-temperature charging of lithium-ion cells.

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ABSTRACT

Lithium-ion cells, especially when used in electric vehicles at varying operation conditions, require a sophisticated battery management to ensure an optimal operation regarding operation limits, performance, and maximum lifetime. In some cases, the best trade-off between these conflictive goals can only be reached by considering internal, non-measurable cell characteristics. This article presents a data-driven model-reduction method for a strict electrochemical model. The model describes the charging process of a lithium-ion cell and possibly occurring degradation effects in a large temperature range and is presented in Part I of this contribution. The model-reduction process is explained in detail, and the gained model is compared to the original electrochemical model showing a very high approximation quality. This reduced model offers a very low computation complexity and is therefore suitable for the implementation in a battery management system (BMS). Based on this model, an advanced charging strategy is presented and evaluated for possible reductions in charging times especially at low temperatures.

1. Introduction

Lithium-ion batteries are a key component in current and prospective electric vehicles. For an appropriate operation of these batteries which has to ensure high performance and long lifetime, monitoring of the cells is essential. On the one hand, the available power and the resulting possible driving range in the present operation point have to be determined. On the other hand, the state-of-health (SOH) of the cells has to be identified since aging (i.e. degradation of the battery) can occur due to different reasons. To recognize degradation, usually the effects of aging, i.e. a loss of capacity or a rise of the internal resistance, are monitored [1].

As cell degradation is strongly depending on the operation conditions, an operation strategy preventing or reducing degradation is necessary beyond cell monitoring. In simple cases, this can be reached through operation limits usually depending on measurable signals, e.g. current or temperature of the cells. However, extended operation strategies require a more accurate understanding and description of the degradation mechanisms.

One method of gaining this knowledge on degradation is strict electrochemical modeling, which allows a deeper insight in non-measurable cell characteristics, e.g. anode potential as indicator for metallic lithium deposition (lithium plating) during charging. Such an electrochemical model describing the charging process of lithium-ion cells at low temperatures is worked out in Part I [2] of this contribution. In detail, a 1D + 1D (pseudo-2D) model based on [3,4] calculating the lithium-ion concentration in surface and particle radius direction is set up over a wide temperature (−25 °C to

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40 °C) and current range (0.1 C–6 C). This temperature and current range even exceeds the operation range relevant for the assessment of charging at low-temperatures. Additionally, the complex model is parameterized and validated with cell measurements and analyzed regarding the ability to predict harming cell states.

Advanced operation management or diagnosis methods based on such electrochemical models allow to use additional, non-measurable information from within the model, but require that these models are calculated online. Hence, for the application within a model-based on-board control avoiding adverse system states, a reduction of the complex model is necessary to fulfill the challenging computational and real-time requirements of the battery management system (BMS). These are, in detail, a low complexity model with focus on good approximation of the original electrochemical model for the selected signals, a realization in a discrete-time not requiring a solver, and, as a result, a low execution time.

A model reduction can be performed e.g. through approximations and mathematical simplifications. In these model reduction steps, the original electrochemical character of the model is retained and only the level of abstraction is enlarged. This leads to a reduction of the model complexity, but not necessarily to a reduction of the computational load.

In this contribution, model-reduction based on system identification methods is introduced, resulting in models for terminal voltage and anode potential prediction. These models are identified from input and output signal data sets retrieved from the original electrochemical model. Thus, the reduction of the model is done implicitly by approximating the input/output behavior. To yield a good approximation, the input signals for the generation of data sets by simulation have to show a high excitation and cover the whole state-of-charge (SOC) and temperature range of the validated electrochemical model. Using this simulation data, each model is identified fulfilling the given on-board requirements. A discrete-time linear parameter-varying (LPV) model is chosen as model form, because these models are known to reproduce well the complex nonlinear behavior of lithium-ion battery cells and still fulfill these requirements [5].

With the reduced anode potential model, it is possible to simulate the anode potential at the anode-separator interface. In Ref. [2], this potential is shown to give the best indicator for a degradation during charging. Therefore, as an additional contribution of this paper, this model is used to develop an advanced charging control preventing degradation and still delivering maximum performance at every operation point.

The paper is organized as follows: The proposed model reduction method is presented in detail in Section 2. The reduced models are assessed and compared to the original electrochemical model in Section 3. The application of the gained anode potential model within an advanced charging strategy is discussed in Section 4. The contribution closes with conclusions and an outlook on further work in Section 5.

2. Model reduction

In literature, reduction of electrochemical models yielding an on-board applicable model with low complexity is commonly done by mathematical simplifications based on approximations and a higher abstraction level, see e.g. Refs. [6–9]. The resulting reduced models are still physically motivated. However, the equivalence of the original and the reduced model for one parameter set is not guaranteed for a given cell, and in some cases parameters of the reduced model have to be fitted due to the approximations, resulting in a limited physical meaning. Additionally, these models are still continuous-time descriptions and therefore require solver functions, which is a serious drawback for on-board implementations. If it is possible to transform such a reduced model to an equivalent discrete-time formulation with fixed sample time, the physical meaning of the parameters gets lost.

In contrast to this classical approach which retains the basic physical-electrochemical structure of the model, the proposed method focuses on the discrete-time approximation of the input/output behavior of the original model, whereas the structure of the underlying model is arbitrary, as long as it fulfills the requirements of on-board applicability. This model reduction approach is based on the idea of black-box system identification [10], where the discrete-time input/output behavior of a dynamical system with unknown internal structure and parameters (a “black box” we have no insight into) is estimated from measurement data sets of the input and output signals. Instead of measurements of inputs and outputs of a system, simulated data from the original electrochemical model is used in this work to build the data sets required for the identification process, which in this case yields the reduced and discrete-time model description with a structure independent of the original model’s internal structure. The choice of model structure leaves more degrees of freedom to fit the input/output behavior well even with very simple models. In Refs. [11,12], a related identification-based approach was used to retrieve a reduced electrical model of a solid oxide fuel cell (SOFC).

The specific electrochemical model used in this work is described in Part I [2] and was implemented in COMSOL. The common interface of the original electrochemical model and each of the two application-oriented reduced models are the input and output signals. These signals are the applied current I, the initial SOC, and the cell temperature T as inputs as well as the terminal voltage U or the potential vs. Li/Li^+ at the anode-separator interface ϕ as outputs, respectively. The latter is chosen from the numerous signals available in the space-resolved electrochemical model as it is most suitable and also sufficient to indicate degradation during charging processes due to metallic lithium deposition. For charging processes, this point of the anode will always be the one with the lowest potential as described in Part I of this contribution [2].

In Subsection 2.1, the basic structure of the reduced cell models is introduced, where the output signals are assumed to be the superposition of a static and a dynamic model part. A detailed description of the identification data is given in Subection 2.2. Subspace identification, which is one possible method for black-box system identification, is introduced and utilized in Subection 2.3 to identify the dynamic parts of the reduced models from the identification data sets. As this identification is done separately for

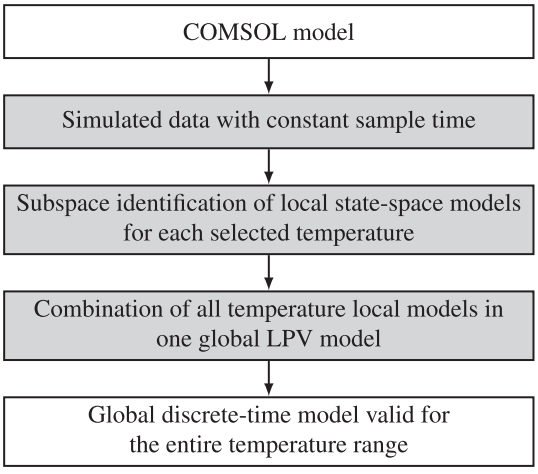

Fig. 1. Overall schedule of the model reduction process using system identification.