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Extended operating range for reduced-order model of lithium-ion cells

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HIGHLIGHTS

- Battery-management systems require accurate cell models over a wide operating range.
- A previously reported physics-based model is accurate over only a narrow range.
- We use model blending to extend the operating window of the physics-based model.
- We show that the blended model is stable and accurate over a broad operating range.

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ABSTRACT

In a previous paper, we developed a method to produce a physics-based one-dimensional discrete-time state-space reduced-order model (ROM) of a lithium-ion cell. The method relies on linearizing the standard porous-electrode equations around a fixed state-of-charge (SOC) and operating temperature setpoint. The ROM is able to track a highly dynamic input accurately near the linearization setpoint, but its performance degrades as either the cell's SOC or temperature move away from this linearization point.

This paper describes a way to extend the accuracy of the ROM over a wide range of SOCs and temperatures using a model-blending approach. Our results demonstrate that the approach accurately models the cell's voltage and internal electrochemical variables over a wide range of temperature and SOC, with little added computational complexity.

1. Introduction

Battery chargers and battery-management systems rely on mathematical models of their battery cells to be able to determine dynamic operational limits within which the battery pack may be safely operated. Current battery-management systems use equivalent circuit models [1]. The advantage of these models is that they are simple enough computationally to be incorporated into real-time control systems, and thus can be used in methods to estimate many cell properties such as state-of-charge (SOC) and state-of-health, as well as voltage-based power limits (see, for example, [2–4]).

Equivalent-circuit models can produce accurate predictions of cell voltage; however, they do not provide insight into the internal electrochemical variables of the cell. On the other hand, porous-electrode models do have this ability. Doyle, Fuller, and Newman [5,6] have developed such a physics-based porous-electrode model, which comprises coupled nonlinear partial-differential equations (PDEs). This model describes the electrochemical internal dynamics of the cell in addition to being able to predict cell voltage.

Control algorithms based on knowledge of the internal electrochemical state have the potential to expand the performance and extend the life of cells. They can predict power limits with respect to electrode surface depletion/saturation conditions and with respect to side reactions responsible for damage and sudden loss of power [7,8]. For example, it is shown in Ref. [9] that electrochemically limited pulse charging a 6 Ah cell to the same negative-electrode phase-potential $\phi_s - \phi_e$ at the negative-electrode/separator boundary as encountered at equilibrium at 100% SOC increases usable charge power by 22% and usable energy by 212% versus voltage-limited charging.

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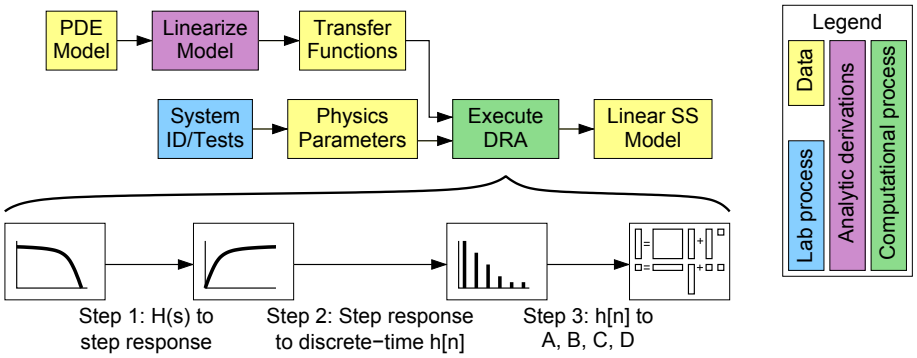

Fig. 1. Approach to generating the linear state-space model.

However, the computational complexity of the porous-electrode PDE models precludes their use by real-time control systems. Instead, accurate reduced-order approximate models, which can predict both the cell voltage and internal electrochemical variables, are needed. Over a series of papers, we are presenting a methodology to develop such models.

The first paper in the series introduced the "discrete-time realization algorithm" (DRA) as a method for converting a transcendental transfer function into a discrete-time state-space reduced-order model [10]. It is further shown in Ref. [10] that the resulting model is a globally optimum p-rank approximation to the transfer function it approximates, by the Schmidt–Mirsky theorem [11]. The second paper showed how to find transcendental transfer functions corresponding to lithium-ion internal cell dynamics [12]. The scope of the work in the second paper was limited to showing how to create an ROM that is linearized to give accurate predictions around a single SOC and temperature set-point only. This ROM was able to predict cell voltage as well as cell potentials $\phi_s(x,t)$ and $\phi_e(x,t)$, lithium concentrations $c_{s,e}(x,t)$ and $c_e(x,t)$, and intercalation flux $j(x,t)$ for any desired combination of one-dimensional internal cell locations x. This was accomplished using a fifth-order linear discrete-time state-space model, plus some nonlinear algebraic corrections. The resulting reduced-order model (ROM) is simple enough computationally for use in real-time estimation of the electrochemical variables. Our results demonstrated that the ROM performs well if the temperature remains constant and the SOC does not vary significantly from the linearization point.

This paper is the third in the series of planned works. Here, we present a method to extend the accuracy of the model over a wide range of both SOC and operating temperatures. We accomplish this by generating individual models at specific states-of-charge and temperatures and then blend the models using the real-time estimates of the SOC and temperature. A planned fourth paper will show how to incorporate heat generation and heat flow into the model.

The paper is organized as follows. In Section 2, we review the approach used to produce the discrete-time reduced-order model at a particular operational setpoint, and how to apply this model to an arbitrary current input. In Section 3, we discuss the impact of changing temperature and SOC on each ROM. In Section 4, we describe the specific implementation of the proposed model-blending approach, and demonstrate that this approach produces a stable system. Results using three different current and temperature scenarios are presented in Section 5.

2. Background: the single setpoint ROM

An overview of the steps required to generate a physics-based reduced-order linear state-space model at a specific operating setpoint is illustrated in Fig. 1. The first step is to determine the physics parameters of the cell, which include factors such as electrode and particle dimensions, conductivities, diffusivities, porosities, open-circuit-potential relationships, and so forth. These parameters are found either by direct measurements and electrochemical experiments or, in the cases where that is not feasible, by running tests on the cell and using system identification techniques to estimate the parameter values. The values of these physical parameters are input to the PDE porous-electrode model equations, which are represented as "PDE Model" in the figure. These equations describe the electrochemical dynamics of the cell and allow us to solve for five electrochemical variables within the cell: the reaction flux $j(x,t)$, solid and electrolyte lithium concentration $c_{s,e}(x,t)$ and $c_e(x,t)$, and solid and electrolyte potentials $\phi_s(x,t)$ and $\phi_e(x,t)$. These nonlinear coupled PDEs can be solved using finite-element software, for example, but this is computationally too complex for use in a real-time controller. Instead, we must find a reduced-order model.

In the next step, we follow the approach introduced in Refs. [7,13] and convert the PDE model into transcendental transfer functions after making two simplifying assumptions: 1) that the potential in the electrolyte is not dependent on the concentration of lithium in the electrolyte, and 2) that the nonlinear equations can be linearized. We then derive closed-form Laplace-domain transcendental transfer functions from these linearized equations. The discrete-time realization algorithm (DRA), based on the Ho–Kalman algorithm [14], is used to convert these transcendental transfer functions into an optimal discrete-time state-space realization. A detailed description of the DRA is given in Ref. [10]. A brief summary of the steps is as follows:

1. Sample the continuous-time transfer function in the frequency domain at a high rate, and take the inverse discrete Fourier transform (IDFT) to get an approximation to the continuous-time impulse response. Then, form the continuous-time step response from the continuous-time impulse response.
2. Compute the discrete-time pulse response values from the continuous-time step response, assuming a sample and hold circuit connected to the system input.
3. Generate a discrete-time state-space realization using the deterministic Ho–Kalman algorithm. This algorithm returns the reduced-order **A**, **B**, and **C** matrices from the discrete-time pulse-response sequence in Step 2. The order of the system is determined from the sorted singular values of the Hankel matrix that is computed as part of the algorithm. The **D** matrix is found by the initial value theorem.

The resulting ROM comprises a linear dynamic part and some algebraic nonlinear corrections. The optimal reduced-order discrete-time linear state-space model has the form