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A lumped-parameter electro-thermal model for cylindrical batteries

Xinfan Lin [a,*], Hector E. Perez [a], Shankar Mohan [b], Jason B. Siegel [a],
Anna G. Stefanopoulou [a], Yi Ding [c], Matthew P. Castanier [c]

[a] Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI 48109, USA
[b] Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109, USA
[c] U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC), Warren, MI 48397, USA

HIGHLIGHTS

- An electro-thermal model capturing battery SOC, voltage, skin and core temperature.
- A convenient parameterization method identifying the two sub-models separately.
- Validation of the identified model with electrochemical impedance spectroscopy.
- Experimental validation with cycles covering 20–100% SOC, 5–38 °C, and max C-rate 20C.

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ABSTRACT

Combining several existing lumped-parameter models, this paper presents an electro-thermal model for cylindrical batteries. The model consists of two sub-models, an equivalent-circuit electrical model and a two-state thermal model which are coupled through heat generation and temperature dependence of the electrical parameters. The computationally efficient 5-state model captures the state of charge (SOC), terminal voltage, surface temperature and the often neglected core temperature of a battery for wide range of operating conditions. The proposed parameterization scheme allows separate identification of the electric and thermal sub-models, greatly reducing the complexity of the parameterization process. The methodology is applied to a $LiFePO_4$/graphite battery. Comparison with the electrochemical impedance spectroscopy data clarifies the frequency range of the model fidelity. The model is further validated with two drive-cycle tests, covering SOC range 25%–100%, temperature 5 °C–38 °C, and maximum C-rate of 22*C*.

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1. Introduction

Vehicle electrification, including application of hybrid electric vehicles (HEV), plug-in electric vehicles (PHEV) and battery electric vehicles (BEV), has been considered as a promising solution to the upcoming energy and environmental issues. Among all types of batteries, lithium ion batteries are nowadays widely used for automotive applications due to their advantages in energy/power density, charge efficiency among others. Correct estimation of the electrical and thermal dynamics of batteries is critical for safe and efficient operation. Model based observers have been widely considered for such purpose, where electrical models are used to estimate the state of charge (SOC) and voltage [1–3], and thermal models are applied for temperature monitoring [4–7].

The criteria for judging the quality of a control-oriented model include model fidelity, computational efficiency and ease of parameterization. Existing electrical models vary in complexity and fidelity. In some applications, where the applied current is small and simple, a coulomb counting-based OCV-R model is sufficient [8]. Such model consists of an SOC-dependent open circuit voltage (OCV) and an ohmic resistance. More complicated models, such as partial differential equation (PDE)-based electrochemical models [9–11], have also been used to capture the electrochemical processes during battery operation, giving more accurate voltage estimation over a wide range of current inputs. However, these models are computationally intensive and difficult to parameterize [12]. To balance complexity and fidelity, equivalent circuit models [1,13,14] are widely adopted in battery management systems (BMS),

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* Corresponding author.
E-mail address: xflin@umich.edu (X. Lin).

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where a series of resistor-capacitor (R–C) pairs are used to capture the voltage dynamics.

For temperature estimation of the cylindrical battery, existing PDE-based thermal models can predict the detailed temperature distribution throughout the battery [10,15,16]. However, like the electrochemical models, these models are not easy to compute in real time and parameterize. Therefore, single-state models, where the thermal dynamics are represented by a bulk temperature [17,18], have been widely used due to their computational efficiency. Nevertheless, such approximation might lead to over-simplification since the temperature in the battery core can be much higher than in the surface [19]. Two-state thermal models capturing both the surface and the core temperatures have also been studied in Refs. [6,19–21]. Such models are capable of estimating the core temperature, and are efficient for control practice due to their limited number of states.

Electro-thermal models constructed by combining the electrical and thermal models introduced above have also been studied broadly. Some of these works are conducted with pure PDE-based approaches, such as [15,22], where an electrochemical model is coupled with a heat-equation based thermal model. Some apply lumped models to capture both the electrical and thermal dynamics, such as [23] (equivalent-circuit electrical model + single-state thermal model), and [4] (equivalent-circuit + lumped thermal model along the longitudinal direction). Others apply mixed approaches. For example, in Refs. [10,24], the electrical dynamics are modeled by an electrochemical model, and a single-state thermal model is used to capture the bulk temperature.

In this paper, a new control-oriented electro-thermal model is formulated by integrating an equivalent-circuit electrical model with a two-state thermal model. The thermal model captures the surface and core temperatures as the two states. Compared with the single-state model, this model provides higher fidelity with minimal increase in complexity, and it is more computationally efficient than the PDE-based models. Parameters of the electrical model are dependent on temperature, SOC and current direction. As a result, model parameterization can be computationally expensive and time consuming, requiring large dataset and advanced optimization methods, such as the genetic algorithm [1]. The parameterization strategy developed in this paper allows separate identification of electrical and thermal parameters in a straightforward way by isolating the dynamics of each sub-model. The electrical parameters are first identified under isothermal and SOC-invariant conditions for different temperatures, SOCs and current directions, similar to the method in Ref. [25]. The thermal model is then parameterized with a drive-cycle test using the heat generation calculated based on the current and voltage measurement and the open circuit voltage in the electrical model. The designed method has been applied to an A123 $LiFePO_4$/graphite battery. As an extension of [26], in this paper, frequency response of the modeled voltage dynamics is studied by comparing the model impedance with the electrochemical impedance spectroscopy (EIS) measurement. The identified electro-thermal model is also validated by two drive-cycle tests. Good model fidelity is achieved under high current, shown by a drive-cycle test with maximum current rate of 22C and temperature variation between 25 °C and 38 °C.

2. Coupled electro-thermal battery model

In this section, a coupled electro-thermal model is formulated for cylindrical batteries. The terminal voltage is captured by an equivalent circuit model, and a two-state thermal model is adopted to estimate the core and surface temperatures. The parameters of the electrical model depend on temperature, SOC and current direction, while the thermal parameters are treated as constant.

2.1. Electrical model

The schematic of an equivalent circuit model is shown in Fig. 1. Under a current I (positive for discharge), the terminal voltage V_T is modeled in three parts as

$$V_T = V_{OCV} - IR_s - \sum_{i=1}^{n} V_{RC,i}. \tag{1}$$

The first part is the open circuit voltage, V_{OCV}, which is usually a nonlinear function of SOC. The SOC is calculated by coulomb counting as

$$\frac{dSOC}{dt} = -\frac{1}{C_{bat}} I, \tag{2}$$

where C_{bat} is the battery capacity. The second part is the voltage drop over a series resistor R_s, accounting for the ohmic resistance. The last part is the voltage drop across a series of parallel R–C circuits, $V_{RC,i}$, which are used to approximate the voltage dynamics during transients. The dynamics of each R–C pair, $V_{RC,i}$, are described as

$$\frac{dV_{RC,i}}{dt} = -\frac{1}{R_i C_i} V_{RC,i} + \frac{1}{C_i} I, \tag{3}$$

where R_i and C_i are the equivalent resistance and capacitance. Typically, the values of R_i and C_i vary with SOC, current direction, and temperature which is captured by the thermal model to be introduced in Section 2.2. It will be shown in Section 3.1 that inclusion of more R–C pairs improves the model fidelity at the cost of complexity.

2.2. Two-state thermal model

By assuming longitudinal homogeneity, a two-state model [6,20], as shown in Fig. 2, is used to capture the lumped thermal dynamics of a cylindrical battery. Governing equations of T_c and T_s are [6,20],

$$\begin{aligned} C_c \frac{dT_c}{dt} &= Q + \frac{T_s - T_c}{R_c} \\ C_s \frac{dT_s}{dt} &= \frac{T_f - T_s}{R_u} - \frac{T_s - T_c}{R_c}. \end{aligned} \tag{4}$$

The heat generation Q in Eq. (4) is a byproduct of the chemical reactions taking place in the electrode assembly during battery operation. The value of Q is calculated based on the electrical model, as

$$Q = I(V_{OCV} - V_T), \tag{5}$$

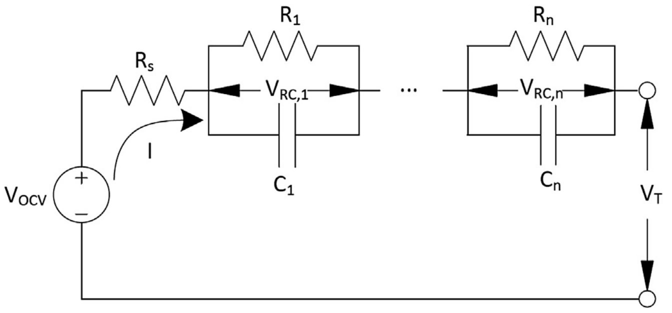

Fig. 1. Schematic of the equivalent circuit model.

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