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Infinite-Dimensional Boundary Observer for Lithium-Ion Battery State Estimation

Agus Hasan* and Jerome Jouffroy

Center for Unmanned Aircraft Systems
Mærsk McKinney Møller Institute, University of Southern Denmark, 5230 Odense, Denmark

Abstract

This paper presents boundary observer design for state-of-charge (SOC) estimation of lithium-ion batteries. The lithium-ion battery dynamics are governed by thermal-electrochemical principles, which mathematically modeled by partial differential equations (PDEs). In general, the model is a reaction-diffusion equation with time-dependent coefficients. A Luenberger observer is developed using infinite-dimensional backstepping method and uses only a single measurement at the boundary of the battery. The observer gains are computed by solving the observer kernel equation. A numerical example is performed to show the applicability of the design.

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Keywords: Distributed parameter systems; observer design; lithium-ion battery; battery management systems.

1. Introduction

Lithium-ion batteries are one the best commercially available power source for energy storage systems for renewable sources, e.g., computers, electrified transportation, and unmanned aerial vehicles (UAVs). The reason is partially because lithium-ion batteries offer the highest power and energy density, which make them better than nickel cadmium or lead acid cells. However, their reliability is impacted by discharge rate, temperature, and amount of usage. Furthermore, they have short cycle lives, significant degradation with age, and can become unsafe if

* Corresponding author. Tel.: +45 93507327; fax: +45 66157697.
E-mail address: agha@mmmi.sdu.dk

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overheated. A smart battery management system based on state-of-health (SOH) and state-of-charge (SOC) can recognize these factors, enable users and operators the information they need for safer operation.

This paper focuses on lithium-ion battery SOC estimation. SOC is defined as the ratio of instantaneous remaining battery charge to its maximum capacity. Lithium-ion battery SOC estimation is a challenging problem since the battery dynamics are governed by thermal-electrochemical principles, which mathematically modeled by partial differential equations (PDEs). A thermal-electrochemical model consists of a set of PDEs, which is a Single Particle Model (SPM) to model the anode, cathode, and electrolyte dynamics, and an ordinary differential equation (ODE) to model the average temperature of a lithium-ion battery. In general, the thermal-electrochemical model is a coupled of time-varying reaction-diffusion equations and an ODE.

1.1. Literature review

Control and estimation of PDEs have gained much attentions lately, due to the introduction of the backstepping technique [1]. The method uses an integral transformation to transform the system into a stable target system. The method has been successfully used to solve control and estimation problems of many types of PDEs including pseudo-parabolic equation [2,3], KdV equation [4], and PDE-ODE cascade systems [5]. More recently, the method has been used to design a stabilizing controller for a reaction-diffusion equation with spatially-varying coefficients [6]. In the petroleum industry, the backstepping method has found several applications, such as in gas coning control [7], flow control in porous media [8,9], slugging control [10], lost circulation and kick control [11,12,13], and heave attenuation problem [14,15]. Another emerging application is in battery management system (BMS), where the backstepping method is used to design a Luenberger observer for state estimation of a lithium-ion battery [16,17]. In [18], a backstepping observer is used for state estimation of a single particle model with electrolyte dynamics. In this work, the diffusion coefficients are assumed constant. An improved model using a thermal-electrochemical model is considered in [19,20]. Here, the diffusion coefficients are considered to be of an Arrhenius-like dependency on temperature.

1.2. Contribution of this paper

The novelty of this paper is a state observer design for a reaction-diffusion equation with space and time dependent coefficient using a single boundary measurement. Furthermore, we implement the boundary observer design for SOC estimations in lithium-ion batteries from a thermal-electrochemical model.

1.3. Organization of this paper

In section 2, the estimation problem for a reaction-diffusion equation is formulated. The main contribution of this paper is presented in section 3. Here, we design a state observer for the reaction-diffusion equation with space and time dependent using the backstepping method with only a single boundary measurement. In section 4, an observer design for a thermal-electrochemical model used in the lithium-ion battery SOC estimation is presented. A simulation is presented to demonstrate the usefulness of the observer design. Finally, section 5 contains conclusions.

2. The Space and Time Dependent Reaction-Diffusion Equation

We consider the following a space and time dependent reaction-diffusion equation with mixed boundary conditions

$$
\begin{aligned}
&\frac{\partial c}{\partial t}(r,t) = D(r,t)\frac{\partial^2 c}{\partial r^2}(r,t) + \lambda(r,t)c(r,t) \\
&c(0,t) = 0 \\
&\frac{\partial c}{\partial r}(1,t) = H(t)c(1,t) + M(t)
\end{aligned}
\tag{1}
$$

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