A Study of Recursive Techniques for Robust Identification of Time-Varying Electrical Equivalent Circuit Models of Li-Ion Batteries

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ABSTRACT

This article presents results of a comparative study of recursive techniques for robust identification of time-varying electrical equivalent circuit models of Li-ion batteries. Two such methods are studied, a direct continuous time system identification method and an indirect discrete time technique. The results of this study indicate that although both methods work equally well for identification of time-invariant circuit models from clean voltage-current data, the direct continuous time method outperforms indirect discrete time technique for identification of time-varying circuit models. Similar conclusions can also be drawn for identification of equivalent circuit models in the presence of noise and/or unmodeled dynamics.

KEYWORDS

Continuous Time Identification, Electrical Equivalent Circuit Model, Li-Ion Battery Model, Recursive Parameter Estimation, Robust Identification

INTRODUCTION

An enormous amount of research and development efforts have been spent to date on lithium-ion (Li-ion) battery technology because they are extensively used in most portable consumer electronic devices, electric and hybrid electric vehicles, and industrial instruments as well as machineries. These research efforts have resulted in the development of lithium-polymer cells with very high energy and power densities, which are very attractive for plug-in hybrid and electric vehicle industries.

Modeling of Li-ion batteries is found to be very useful for a wide variety of applications, such as estimation of state-of-charge and state-of-health, optimum battery charger design, and management of battery systems. The available models can be divided into three broad categories, namely, electrochemical, electrical and empirical. A good summary of these models can be found in (Ramadesigan et al., 2012; Chaturvedi, Klein, Chritensen, Ahmed, & Kojic, 2010).

Electrochemical models and their approximations (Doyle, Fuller, & Newman, 1993; Fuller, Doyle, & Newman, 1994; Subramanian, Ritter, & White, 2001; Forman, Bashash, Stein, & Fathy, 2011) are very accurate when used to identify the parameters and constraints in...
that limit a battery cell’s performance, but they are very complex and involve time-varying partial differential equations. They are mostly useful for actual physical design of such batteries. Empirical models (Ramadesigan et al., 2012; Chaturvedi, Klein, Chritensen, Ahmed, & Kojic, 2010) use mathematical methods to predict system level behavior of such batteries, such as battery capacity and efficiency, but they only work for specific applications and often provide inaccurate results. Also, they are not very useful for modeling the voltage-current characteristics of such batteries. Electrical equivalent circuit (EEC) models that use a combination of capacitors, resistors and voltage and current sources have proved to be a reliable way of modeling the voltage-current characteristics of Li-ion batteries. Chen and Mora’s model (2006) is a good example of such models. In view of their modeling accuracy and ease of model identification, EEC models have found widespread applications in estimating a battery’s state of charge (SOC), state of health (SOH), and predicting its end-of-discharge time (Rahimi-Eichi, Baronti & Chow, 2012, 2014; Kim, 2010; Gould et al., 2009; He et al., 2011). In view of this, we focus on EEC models in this paper.

Many applications of EEC models call for an accurate estimation of its model parameters. In addition, the parameter estimation method is required to be robust in the presence of both unmodeled dynamics and measurement noise. The issue of robustness in presence of unmodeled dynamics is important because almost all EEC models represent a reduced order model of a very high order, relatively complex battery system. Similarly, the issue of robustness in presence of noise is also important because most applications call for estimation of model parameters from noisy voltage-current measurements.

A review of EEC modeling literature (related to Li-ion batteries) reveals that the estimation of model parameters is almost always performed using an indirect discrete time (IDT) system identification method. The only exception is the continuous time (CT) modeling and identification methods presented in Xia et al. (2016), which points out the key advantages of CT parameter estimation methods over IDT, including higher accuracy and robustness to high sampling rate, measurement noise and rounding errors. Also, it validates these claims by comparing the results of two CT batch least squares methods and an IDT method.

A comparative study of robustness of direct CT and IDT approaches is also the primary objective of this paper. However, we focus on recursive parameter estimation methods, because battery models represent time-varying systems and batch least squares methods are not useful for estimating their parameters. In addition, we also investigate the robustness of the parameter estimation methods in presence of both noise and unmodeled dynamics. Using voltage-current data from a simulated battery model, we show that a direct CT parameter estimation method offers more reliable estimates of EEC model parameters compared to an IDT method.

This paper is organized as follows. Section 2 summarizes two types of continuous time system identification methods investigated in this paper. Section 3 summarizes a simulated battery model. The main results of this comparative study of two types of parameter estimation schemes are presented in Section 4. Finally, some concluding remarks are given in Section 5.

**CONTINUOUS TIME SYSTEM IDENTIFICATION METHODS**

As mentioned earlier, the main focus of this paper concerns a comparative study of robustness of continuous time system identification methods and indirect DT (IDT) technique. Only a summary of their basic principles is presented here. Details of these methods can be found in (Garnier & Wang,
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