A Piecewise Linear Time-Varying Model for Modeling the Charging and Discharging Processes of a Lithium-Ion Battery

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ABSTRACT

A piecewise linear, time-varying model for modeling the charging and discharging processes of Li-ion batteries is introduced in this paper. Such a model consists of a group of piecewise linear model segments, whose parameters are adapted online over time. Thus, the combined overall model is capable of modeling nonlinear time-varying processes, such as a Li-ion battery charging and discharging processes, quite well. Modeling results of both simulated test data and actual test data gathered from a high-power automotive-grade Li-ion cell are presented. The close matches between actual and model-predicted behaviors demonstrate the effectiveness of the proposed modeling approach and indicate the potential usefulness of such models for a battery management system.

Keywords: Battery Charging Model, Battery Discharging Model, Li-Ion Battery, Piecewise Linear Model, Time-Varying Model

INTRODUCTION

Over the past decade, Li-ion batteries have gained increasing popularity as energy storage devices for a wide variety of applications. They are currently used in most essential portable electronic devices, such as cell phones, laptops, tablets and cameras. Most importantly, they are also used in most hybrid electric vehicles (HEVs) and electric vehicles (EVs).

Compared to other types of batteries, such as Lead-Acid and Nickel-Metal Hydride (Ni-MH), Li-ion batteries have many advantages. They have an excellent charge retention property, high energy density and power density, low self-discharge, high cycle life, a wide variety of choices for positive and negative electrodes for various applications and no memory effects. These properties, as well as decreasing costs, have established Li-ion batteries as a leading candidate for the next generation of automotive and aerospace applications (Braatz, De, Northrop, Ramadesigan, Santhanagopalan & Subramanian, 2012). As oil prices increase and more environmental concerns are raised, the conversion of fuel based vehicles to hy-
brid electric vehicles and electric vehicles is expected to rise with a concomitant increase of the importance of Li-ion batteries.

It is well know that battery models play a very important role in the design, fabrication as well as application of any kind of battery. That is why many different kinds of Li-ion battery models have been developed over the last two decades. A good summary of these models can be found in (Braatz, De, Northrop, Ramadesigan, Santhanagopalan & Subramanian, 2012) and (Ahmed, Chaturvedi, Chritensen, Klein & Kojic, 2010). In general, Li-ion battery models can be divided into three categories: electrochemical, electrical and empirical models. Electrochemical models and their approximations (Doyle, Fuller & Newman, 1993; Doyle, Fuller & Newman, 1994; Subramanian, Ritter & White, 2001; Bashash, Fathy, Forman & Stein, 2011) are very accurate, but very complex because they involve complicated time-varying partial differential equations. Empirical models (Braatz, De, Northrop, Ramadesigan, Santhanagopalan & Subramanian, 2012; Ahmed, Chaturvedi, Chritensen, Klein & Kojic, 2010) use empirical equations or curve-fitting techniques to predict system-level behaviors, such as battery capacity, run-time and efficiency. Finally, electrical models use combinations of capacitors, resistors and voltage and current sources for co-design and co-simulation with other electrical systems. Chen and Mora’s work (Chen & Mora, 2006) provides a good example of electrical models.

None of the above battery models is universally suitable for all kinds of applications. In fact, the specific needs of any particular application dictate the choice of a particular kind of model for any given application. For example, electrochemical models are primarily useful for design of electrochemical cells. They are used to identify the constraints that limit battery cell performance and help in optimizing various other design aspects. On the other hand, electrical models are very well suited for battery run-time prediction, dc response, and state of charge (SOC) estimation.

This paper deals with modeling the charge and discharge processes of Li-ion batteries that can be very useful for a battery management system (BMS). A battery charge-discharge model is one of the key components of a BMS system, because such a model can be used to predict the charge/discharge time of a battery. Based on such predictions, a BMS can optimize the powertrain of a hybrid vehicle. Such an optimized powertrain can improve fuel economy and reduce harmful emissions from a hybrid vehicle.

The charge/discharge models proposed for BMS applications can be grouped into three broad categories, namely, empirical models (Kumar, Saini & Thirugnanam, 2012; Alvarez, Aneiros, Lobo & Lopez, 2013; Chen, Gooi, Xia & Wang, 2012; Ai, En, Lu, Shi & Zhou, 2013), neural network models (Hussein, 2013) and electrical equivalent circuit models (Egardt, Hu & Xiong, 2013). The empirical models are usually not very accurate, and they work for a few specific applications, such as prediction of open-circuit voltage from the state-of-charge of a battery. Also, they may require periodic retuning or recalibration in order to cater for time-variation of battery characteristics. Neural networks also suffer from similar disadvantages, because real-time tuning of such models is not an easy task. On the other hand, the electrical equivalent circuit models seem to work really well for modeling charge or discharge processes of Li-ion batteries (Hussein, 2013). Such models can account for both nonlinearity and the time-varying characteristics of Li-ion batteries quite well. The only drawback of the model proposed in (Hussein, 2013) is its inherent complexity, which motivated us to propose a slightly different, simplified modeling approach here.

This paper introduces a piecewise linear, time-varying model for modeling the charge/discharge process of a Li-ion battery. Such a model is appealing, because the piecewise linear nature of such models can account for the nonlinear characteristics of a battery. Also, the time-adaptive nature of such models account for the time-varying voltage-current characteristics of a battery quite well. Finally, the model
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