ARTICLE IN PRESS

INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2017) 1–8

Available online at www.sciencedirect.com

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Battery dynamic energy model for use in electric vehicle simulation

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ARTICLE INFO

Article history:
Received 27 February 2017
Received in revised form
20 May 2017
Accepted 22 May 2017
Available online xxx

Keywords:
Dynamic model
Batteries
Bond graph
Matlab Simulink
Electric vehicle
Simulation

ABSTRACT

The majority of work carried out around battery models is partly motivated by vehicle simulation. Specifically, for electric vehicle simulation, some characteristics of the battery require more attention while others can be simplified, thus distinguishing dynamic models for battery system simulation slightly and requiring different tools. In this paper, we propose a dynamic battery model that accounts for changes in temperature and can be integrated in electric vehicle simulation for testing purposes by computer simulation. Possibilities shown open the door for extensions of the model according to the needs, using the bond graph formalism and Matlab/Simulink. Comparison with other literature data and experiment made on electric vehicle show the accuracy and the efficiency of this approach.

Introduction

Interest in electric vehicles has grown in recent years as a solution for reducing CO_2 emissions and fossil energy dependence. Automakers are therefore seizing this new market and offering more efficient but considerably more expensive models. These costs are directly related to battery technology, which alone accounts for 1/3 of the cost of the vehicle [1,2]. Batteries in fact have a limited lifetime which makes their use subject to many constraints. Several factors come into play in this issue: temperature, charge/discharge, number of charge/discharge cycles, driver behavior, etc. Simulating and validating the performance envelope of advanced battery packs for electric vehicles is important for the development of hybrid-electric vehicle applications. In-vehicle testing of battery packs can be lengthy and expensive: this is where simulation comes into play. It allows us to predict the behavior of the system under several operating conditions and reduce the number of tests to provide an analysis for a battery pack in real world driving conditions.

Several battery models exist in the literature, ranging from electrochemical models to fully electrical models and several combinations of different methods. Shafiei, Momeni, and Williamson [3] summarize and categorize different battery models with focus on vehicular applications: electrochemical models, stochastic models, analytical models, electrical circuit models (Thevenin-based models, impedance-based models and runtime-based models.) We can group the

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http://dx.doi.org/10.1016/j.ijhydene.2017.05.165

models into three main categories: electrochemical, mathematical and electrical. Electrochemical models are widely used for optimizing the design of the electrodes and the electrolyte as they deal with chemical reactions at the microscopic level of the battery cell. The challenge is the models' slow computation time as it involves differential equations, complex nonlinear and specific information on the chemical properties of the battery which requires long and difficult investigation to obtain.

Mathematical models use mathematical methods such as stochastic approach or empirical equations to predict system behavior levels in terms of efficiency, capacity or autonomy which are needed by battery designers. The downside of these abstract models is that they do not provide current–voltage information for the battery which is important for simulation and optimization. The results are inaccurate with an error margin between 5% and 20%.

Electric models on the other hand have a lower error margin of 1% up to 5%. They juggle between electrochemical and mathematical models using equivalent electrical models and by combining the sources of voltage, resistance and capacity. These models are more intuitive for electricians, practical and easy to handle and implement in circuit simulation. Many models exist that can be divided into three main groups: The Thevenin models, impedance models and performance models.

The Thevenin model assumes that the open-circuit voltage is constant and the battery is modeled as a series combination of the voltage source, a series resistance, and a parallel combination of a capacitor and a resistor. The same is for the impedance based models. The Impedance spectroscopy is used to fit a complicated equivalent network to measured impedance spectra in order to validate the time constants found in the Thevenin models. Increasing the number of parallel RC networks can increase the accuracy of the predicted battery response but prediction errors for estimating run time and SOC tend to be high. These models are then accurate only for a fixed SOC and temperature setting [4].

In Runtime-based electrical models, the continuous or discrete-time implementations are used to simulate battery runtime and dc voltage response in SPICE-compatible simulations for constant current discharges. But as the load currents vary, inaccuracy increases [5].

In most cases it is a combination of these three that provides a model that brings together the advantages of each [5–7]. Most of the work carried out around power system simulation use electric models whether for fuel cell, supercapacitor, lead-acid or lithium ion batteries [8–10].

Based on all the literature presented in the upcoming section, the work detailed in this paper is the development of a dynamic model of a traction battery for the simulation of hybrid-electric vehicles. A dynamic simulation is set up to verify the performance of the developed battery model and the results of simulations carried out to observe changes in battery output characteristics under different charging/discharging, temperature and cycling conditions. Finally, a comparison with data obtained by several studies realized by different authors will validate the model.

Background

Representing the inner interactions within a battery in the form of an electrical network has been commonly used by many researchers. Ceraolo [11] proposes a third-order model formulation and a particular implementation that shows a good compromise between complexity and accuracy, a dynamic battery model lead using modeling equivalent circuits. This approach allowing for the output variables satisfactory system has been widely studied in the literature. However, it does not allow to analyze the effects on the different chemical components of the battery. Another example is the work of Lijun Gao, Shengyi Liu, and Roger A. Dougal [12] who propose a model coded according to the resistive companion method. It approximates all electro-chemical and electro-thermal processes as uniform throughout the entire battery and ignores all spatial variations of concentrations, phase distributions and potentials. It is coded specifically for use in the Virtual Test Bed computational environment. The model deviates from the experimental data at low temperatures and at high discharge rates, using mostly discharge data; and its validity for representing charging processes is unknown. Additionally, Chen and Rincón-Mora [13] create a simplified extracted electrical battery model ignoring self-discharge, cycle number, and temperature to predict runtime and I–V performance. In other work by Mischie and Stoiciu [14] the dynamic model takes into account the changes in the received or delivered battery current.

Regarding the electric vehicle application, Tremblay, Dessaint, and Dekkiche [15] developed a battery model that can be applied to dynamic simulation software. The simulation model uses only the battery state-of-charge (SOC) as a state variable in order to avoid the algebraic loop problem on simulation tools. Kroeze and Krein [5], on the other hand, present a multiple time-constant battery model for use in dynamic electric vehicle simulations for predicting SOC, terminal voltage, and power losses of different type of batteries. So did Erdinc, Vural and Uzunoglu [6] with their dynamic model of lithium-ion battery developed with MATLAB/Simulink and that allows to observe the changes in battery terminal output voltage under different charging/discharging, temperature and cycling conditions. In Ref. [5], the battery terminal voltage variation was calculated by taking into account transient and steady state behavior of internal resistance of the battery with respect to SOC for a dynamic battery model for hybrid vehicles.

In this work, we focus on electrical dynamic models. Instead of considering the individual components of the battery or only its behavior as seen from the terminals, a different approach is adopted that consists of modeling the energy flow absorbed and delivered by the battery. This model will not only analyze the electrical and thermal behavior of the battery during charging and discharging, but can also be integrated later in as an independent block on a hybrid-electric vehicle dynamic model to be assembled in the desired configuration and will assist with appropriate design of the battery in vehicle operation and system analysis.

Please cite this article in press as: Benabdelaziz K, Maaroufi M, Battery dynamic energy model for use in electric vehicle simulation, International Journal of Hydrogen Energy (2017), http://dx.doi.org/10.1016/j.ijhydene.2017.05.165