Journal of Power Sources 256 (2014) 410–423

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Review

A survey of mathematics-based equivalent-circuit and electrochemical battery models for hybrid and electric vehicle simulation

Aden Seaman [a,*], Thanh-Son Dao [b], John McPhee [a]

[a] *Systems Design Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada*
[b] *Maplesoft, 615 Kumpf Drive, Waterloo, ON N2V 1K8, Canada*

HIGHLIGHTS

- Present a survey of equivalent-circuit and electrochemical Li-ion battery models.
- Aimed at modelling hybrid and electric vehicles.
- Cover models that include effects like state of health and temperature.
- Help researchers get oriented with battery models and modelling techniques.

ARTICLE INFO

Article history:
Received 13 August 2013
Received in revised form
2 January 2014
Accepted 16 January 2014
Available online 14 February 2014

Keywords:
Battery
Model
Circuit
Electrochemical
HEV

ABSTRACT

In this paper, we survey two kinds of mathematics-based battery models intended for use in hybrid and electric vehicle simulation. The first is circuit-based, which is founded upon the electrical behaviour of the battery, and abstracts away the electrochemistry into equivalent electrical components. The second is chemistry-based, which is founded upon the electrochemical equations of the battery chemistry.

1. Introduction

Battery modelling is a challenging field that has been receiving a great amount of interest recently due to two main commercial drives: the desire for longer-lasting portable electronic devices [1–3], and the great push for hybrid and battery electric vehicles by the automotive industry [4,5].

These two industries have different aims. The portable electronics industry is concerned with maximizing the operating life of a low-power electronic device that runs for a long period of time on a small inexpensive battery pack. The electric vehicle industry is concerned with maximizing the driving range and fuel economy of hybrid and electric vehicles using large battery packs in demanding applications that involve high power charge and discharge rates that push the batteries to their limits, while operating within a range that maximizes the expensive battery pack's service life.

In both of these areas, accurate and efficient battery modelling is vital to help maximize the performance of a device and its battery, and to inform the development of electronic and control systems. The overall performance and life of the device depends on the control system and electronics that interface with the battery, which need to be carefully tailored to the behaviour of the battery. Furthermore, the size and configuration of the battery pack must be chosen to maximize the performance of the device while minimizing its cost.

In this paper we focus on the field of battery modelling for automotive electric vehicle simulation, with an aim to help engineers and scientists become familiar with the field of battery modelling and the different models and techniques that are commonly used. Because the field of battery modelling is so extensive, we limit ourselves to considering only the most common battery chemistries and modelling techniques.

---

* Corresponding author. Tel.: +1 519 888 4567; fax: +1 519 746 4791.
E-mail addresses: adenseaman@alumni.uwaterloo.ca (A. Seaman), dthanhson@gmail.com (T.-S. Dao), mcphee@uwaterloo.ca (J. McPhee).

http://dx.doi.org/10.1016/j.jpowsour.2014.01.057

We also limit ourselves to acausal, physics-based battery models. This means our batteries use voltage, current, and temperature as the physical quantities of interest, and that they can be written as a system of continuous-time equations. This is in contrast to causal, signal-based battery models that typically use discrete-time equations in an iterative solution, and power as the main physical quantity of interest.

The most commonly used batteries in electric vehicles today are the Nickel-Metal-Hydride (NiMH) and Lithium-Ion (Li-ion) chemistries [6]. In the past, Lead-Acid batteries (PbA) were used, but these are falling out of favour to the higher energy and power densities of the Ni-MH and Li-ion chemistries. However many of the techniques developed for modelling these PbA batteries are applicable to more modern chemistries. In the future, Li-ion is a very promising chemistry that is light weight and has high energy and power densities; however more research needs to be done to drive down the cost of these batteries and to increase their safety [6] and performance, particularly at relatively high and low temperatures.

In Section 2 we survey battery models as they apply to various battery modelling tasks. Section 3 focuses on equivalent circuit models in particular, and surveys different modelling techniques and considerations. Section 4 surveys electrochemical battery modelling, and Section 5 briefly compares an equivalent circuit and electrochemical battery under pulse discharge, shows the results of a sensitivity analysis of the two battery models, and finally shows the results of an electric vehicle simulation. The paper is finished off by the conclusions, acknowledgements, references, and appendices.

2. Battery modelling

The two most common techniques we encountered for modelling batteries in automotive applications are equivalent electric circuit and electrochemical modelling. Some models [7–9] combine elements of both chemistry and circuit-based modelling techniques.

Equivalent circuit modelling techniques abstract away the electrochemical nature of the battery and represent it solely as electrical components [1]. Sometimes these contain non-linear components like diodes that strive to better approximate the electrochemical nature of the battery. The structure of the model depends on the type of experimental method used to determine the parameters of the model – which is usually either electrochemical impedance spectroscopy or measuring pulse discharge behaviour – as well as the desired fidelity and goals of the modelling effort.

Electrochemical modelling techniques are all based on the highly non-linear equations that describe the electrochemical physics of the battery, and employ many different approximations to simplify the equations and the solutions thereof, depending on the level of fidelity one requires and the goals of modelling the battery.

Generally, the simpler the model, the faster it will simulate, but the lower its fidelity. This is an important trade-off that one must consider when choosing a battery model to suit one's application, particularly if real-time simulation is a requirement.

Although a comprehensive comparison of different models would be challenging due to the wide variety of phenomena different models are good at capturing, comparing similar models is possible. Zhang and Chow [10] do a computational-complexity versus modelling-error analysis for a Thévenin resistor–capacitor network circuit model, varying the number of RC pairs. Increasing the number of RC pairs decreases the error and increases the computation time, and this paper shows how these quantities scale as a function of RC pair number.

For real-time control system applications, where high fidelity models are often not required, simple circuit based models are employed [11–14]. However for applications requiring higher fidelity such as vehicle performance, drive cycle simulations, battery ageing, and other computation-intensive simulations, a higher fidelity circuit-based or chemistry-based model can be used to increase the accuracy of the results. Thus, the choice of the right battery model to use depends on the fidelity one requires for one's application.

For on-line state of charge (SOC) estimation, battery models are usually fairly simple, as they are fused with an actual battery using a technique like an Extended Kalman Filter (EKF) [15–17], a fuzzy-logic system [18,19], a least-squares regression model [20], or a sliding-mode observer model [21]. What is usually required in these applications is that the model be simple enough to run on an embedded controller while being accurate enough to model the battery's internal variables of interest, primarily the SOC [22].

For control system development, battery models can again be fairly simple. Being able to run in real-time and on embedded computers is an important requirement for control systems, so the battery models cannot be too computationally expensive. The majority of these models are circuit-based, comprising either a simple resistor, or a Thévenin resistor–capacitor network [11–14].

When doing fuel economy and vehicle performance simulations using drive cycles, more accurate models are desired to fine-tune the performance of the vehicle and power management controller to see how they perform over a long period of time with successive charge and discharge cycles. Since these calculations are usually executed offline on workstations, the stringent requirements of real-time computation are absent, and one can afford to use a more computationally expensive model such as the Li-ion models of [8,10,23–32], the NiMH models of [7,9,23,33], or the lead-acid models of [23,34,35]. A good comparison of circuit-based models for Li-ion batteries is presented by Hu et al. in Ref. [36].

If one is analysing the response of the battery to transients, a model that is based on these measurements and takes the dynamic battery response into account is desired. The Thévenin models of Refs. [13,23,24,26,33] and the electrochemical impedance spectroscopy (EIS) models of Refs. [7,8,22,37–39] are good examples of these. For high frequency switching, a greater number of resistor–capacitor (RC) pairs are necessary to better approximate the short time behaviour of the battery [23]. Alternatively one can model the mostly inductive behaviour of a battery in the high-frequency region using resistor–inductor (RL) networks [40].

An important consideration for electric vehicle applications is the battery's dependence on temperature, especially in cold climates. Because the rate of chemical diffusion is slowed by low temperatures, this can have a serious impact on the current-delivering capabilities of the battery. Although high temperatures have the opposite effect, the downside is that the rate of detrimental electrode oxidization is increased, which shortens the service life of the battery [1,41].

Many battery models do not consider temperature variations. If this is a modelling requirement, then it is necessary to use models like those proposed in Refs. [7–9,25–31,34] that include the effects of temperature on the dynamic response and state-of-charge behaviour of the battery.

State of health (SOH) is a more difficult quantity to measure. It represents the battery's gradual loss of maximum capacity and increase in internal resistance over a long period of time, which eventually results in the battery needing to be replaced. It is due to