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Extraction of battery parameters of the equivalent circuit model using a multi-objective genetic algorithm

Jonathan Brand, Zheming Zhang, Ramesh K. Agarwal*

Department of Mechanical Engineering & Materials Science, Washington University in St. Louis, USA

HIGHLIGHTS

- A simple but accurate battery model based on equivalent-circuit is required.
- Multi-objective genetic algorithm is utilized for extracting performance parameters.
- Battery performance is accurately predicted once parameters are optimally extracted.
- The parameter-extracting code is widely applicable for various types of batteries.
- It can serve as a robust and reliable tool for extracting the battery parameters.

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ABSTRACT

A simple but reasonably accurate battery model is required for simulating the performance of electrical systems that employ a battery for example an electric vehicle, as well as for investigating their potential as an energy storage device. In this paper, a relatively simple equivalent circuit based model is employed for modeling the performance of a battery. A computer code utilizing a multi-objective genetic algorithm is developed for the purpose of extracting the battery performance parameters. The code is applied to several existing industrial batteries as well as to two recently proposed high performance batteries which are currently in early research and development stage. The results demonstrate that with the optimally extracted performance parameters, the equivalent circuit based battery model can accurately predict the performance of various batteries of different sizes, capacities, and materials. Several test cases demonstrate that the multi-objective genetic algorithm can serve as a robust and reliable tool for extracting the battery performance parameters.

1. Introduction

In recent years, there has been tremendous emphasis as well as effort devoted towards the development of high performance batteries mainly driven by their need as a power source for an electric or hybrid electric vehicle [1] and as an energy storage device for intermittent energy supply sources such as solar and wind [2]. Rechargeable batteries are particularly suitable for these applications because of their potential for high round-trip efficiency, long operating life and scalability [3]. In addition to these technical requirements, the battery should be of low enough cost to be cost effective as a power source for an electric vehicle or as an energy storage device.

To study the behavior of electric vehicles, manufacturers model the electric drive train. In order to do so, the energy source of these drive trains, the battery, needs to be accurately modeled as well. There are essentially four types of battery models that are used to model its performance; these can be categorized as the experimental models, the electrochemical models, the mathematical models and the electric circuit based models. The experimental and electrochemical models are not well suited to model the cell dynamics; hence they cannot be used reliably to determine the State-of-Charge (SOC) of the battery [4]. Furthermore, the electrochemical models are computationally expensive and require extensive experimentation for determining the parameters of the model [1]. The mathematical models of the batteries are based on stochastic approaches or empirical equations to predict the run time, capacity and efficiency of the batteries [1]. Furthermore, the mathematical models do not have direct relation between the battery model parameters and the I–V (current–voltage) characteristics of the batteries; hence they have limited use in circuit simulations.

* Corresponding author. 1 Brookings Drive, St. Louis, MO 63130, USA. Tel.: +1 314 935 6091; fax: +1 314 935 4014.
E-mail address: rka@wustl.edu (R.K. Agarwal).

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The electric circuit based or equivalent circuit models (ECM) are the most intuitive for use in circuit simulations. These models are usually based on Thevenin equivalents and impedances. These models are simple and therefore are computationally less intensive. One of the main drawbacks of these models is their inability to predict the lifetime of the battery. However, their simplicity and the ability to predict the $I-V$ characteristics make them suitable for dynamic modeling of the electric vehicles. An ECM comprises of a combination of resistances and capacitors. These parameters are multivariable functions of SOC, current, temperature, number of charge and discharge cycles etc. In order to use ECMs effectively in electric vehicle dynamic simulation, it is critical to determine the parameters of the circuit accurately; these parameters are usually determined by extensive experimentation [5]. In many situations the evaluation of the performance of an electric drive train may require experiments using different type of batteries from different manufacturers. These experiments are generally very resource intensive. Therefore it is generally not feasible to perform experiments for each type of battery to extract parameters for ECM. To overcome this problem, recently Kumar and Bauer [6] have suggested the application of a multi-objective genetic algorithm (MOGA) for extracting the battery parameters.

In this paper, we employ a modified version of the approach outlined in Ref. [6] for extracting the battery parameters and determine the charge and discharge characteristics of five batteries (three industry manufactured batteries and two batteries in research and development stage). The genetic algorithm holds greater benefits compared to other traditional parameter-estimation approaches when analytic solutions of the problem do not exist and when the number of design parameters are large which in this work are 31. The genetic algorithm is also well-known for its minimal requirements of prior knowledge of the solution-searching optimization problem. The computed results are compared with the catalog data (in case of industry manufactured batteries) and the experimental data (in case of batteries in research and development stage).

2. Methodology

Since the equivalent circuit model is described by a set of non-linear equations [5,6], it is not tractable for obtaining an analytical solution. However, the computations employing the solution searching technique can be used to determine the parameter values needed for modeling the batteries. Genetic algorithm (GA) appears to be an ideal candidate for such task. In this work, a modified version of multi-objective non-dominated sorting genetic algorithm (NSGA-II) has been employed [7]. The multi-objective genetic algorithm (MOGA) code was first validated by extracting the battery parameters for the battery [8] used in Ref. [6]; the results were compared with those obtained in Ref. [6]. After the validation, the battery modeling code was employed to extract the battery parameters of two additional industrial lithium-ion batteries [9,10] and the results were compared with the catalog data. Finally the code was applied to extract the optimal parameters of recently proposed high performance batteries, three Li–O_2 batteries [11] and two alkaline batteries with an iron electrode [12] and Potassium Hydroxide electrolyte; these two batteries are in early stage of research and development. For all the five cases, charging and discharging characteristics were obtained which were compared with either the catalog data (for industrial batteries) or with the experimental data (for research domain batteries).

2.1. Equivalent circuit battery model

The schematic of the equivalent circuit model (ECM) used in this work is shown in Fig. 1 [5,6]. The parameters in ECM are identified as the resistances (R_1, R_2), capacitance (C_1), and open circuit voltage of the battery (V_o). The presence of one pair of capacitance and resistance, i.e. C_1 and R_2, makes the model to be linear with time. However, non-linear ECM with more than one capacitance–resistance pairs has also been proposed [13,14], which is supposed to be more accurate in capturing the transient behavior of the battery. Non-linear ECM inevitably introduces more modeling parameters due to the increased model complexity. For simplicity, only the linear ECM shown in Fig. 1 is employed in this paper.

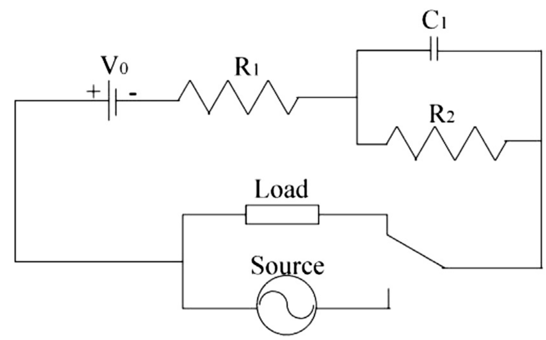

Fig. 1. Equivalent circuit model (ECM) of a battery [5,6].

These parameters are all functions of the current State-of-Charge (SOC) and discharge rate (C_r) of the battery, which can be formulated as following polynomials to account for nonlinear phenomenon in the battery [6]:

Resistance:

$$R_1 = \left(a_1 + a_2C_r + a_3C_r^2\right)e^{-a_7\times SOC} + \left(a_4 + a_5C_r + a_6C_r^2\right) \quad (1)$$

$$R_2 = \left(a_8 + a_9C_r + a_{10}C_r^2\right)e^{-a_{14}\times SOC} + \left(a_{11} + a_{12}C_r + a_{13}C_r^2\right) \quad (2)$$

Capacitance:

$$C_1 = -\left(a_{15} + a_{16}C_r + a_{17}C_r^2\right)e^{-a_{21}\times SOC} + \left(a_{18} + a_{19}C_r + a_{20}C_r^2\right) \quad (3)$$

Open circuit voltage:

$$V_o = -\left(a_{22} + a_{30}C_r + a_{31}C_r^2\right)e^{-a_{23}\times SOC} + \Big(a_{24} + a_{25}\times SOC + a_{26}\times SOC^2 + a_{27}\times SOC^3\Big) - a_{28}C_r + a_{29}C_r^2 \quad (4)$$

In Equations (1)–(4), the coefficients a_1 through a_{31} are model parameters intrinsically determined by the battery and its operational condition, such as the operation temperature.

The time dependent voltage output of the battery cell is then given by the equation [15]:

$$V(t) = \frac{Q_o(0)}{C_1}e^{-t/R_2C_r} + V_o - IR_1 - IR_2\left(1 - e^{-t/R_2C_r}\right) \quad (5)$$

where Q_0 is the nominal capacity of the battery cell (A h), t is time duration since charge/discharge starts (seconds), and I is the current (A).

Equations (1)–(5) describe the performance of a battery by $V(t)$ as a function of SOC, which varies from 0 to 100% of the battery's capacity. Nominal capacity Q_0 is the inherent property of a battery cell, thus it remains constant and can be measured. Charging/