ISA Transactions 66 (2017) 448–459

Contents lists available at ScienceDirect

ISA Transactions

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

State of charge estimation of lithium-ion batteries using fractional order sliding mode observer

Qishui Zhong [a,*], Fuli Zhong [a,*], Jun Cheng [b], Hui Li [a], Shouming Zhong [c]

[a] School of Aeronautics and Astronautics, University of Electronic Science and Technology of China, Chengdu, Sichuan Province611731, PR China
[b] School of Science, Hubei University for Nationalities, Enshi, Hubei Province445000, PR China
[c] School of Mathematical Sciences, University of Electronic Science and Technology of China, Chengdu, Sichuan Province611731, PR China

ARTICLE INFO

Article history:
Received 23 February 2015
Received in revised form
22 March 2016
Accepted 17 September 2016
Available online 15 October 2016
This paper was recommended for publication by Dr. Q.-G. Wang

Keywords:
State of charge estimation
Sliding mode observer
Fractional order RC equivalent circuit model
Lithium-ion battery

ABSTRACT

This paper presents a state of charge (SOC) estimation method based on fractional order sliding mode observer (SMO) for lithium-ion batteries. A fractional order RC equivalent circuit model (FORCECM) is firstly constructed to describe the charging and discharging dynamic characteristics of the battery. Then, based on the differential equations of the FORCECM, fractional order SMOs for SOC, polarization voltage and terminal voltage estimation are designed. After that, convergence of the proposed observers is analyzed by Lyapunov's stability theory method. The framework of the designed observer system is simple and easy to implement. The SMOs can overcome the uncertainties of parameters, modeling and measurement errors, and present good robustness. Simulation results show that the presented estimation method is effective, and the designed observers have good performance.

1. Introduction

Battery which is an important energy storage equipment has been widely used in various electric vehicles (EVs), and plays an important role in EVs [1,2]. Lithium-ion batteries are favored as a promising power source for EVs by the researchers because of the characteristics of high cell voltage, high specific power and long cycle-life [3,4]. In EVs, battery management system was applied to ensure the reliable operations of battery [5], in which state of charge (SOC) is an important parameter [6]. SOC often suffer the influences of random factors like driving loads, operating environment and nonlinear characteristics [7]. Poor SOC estimation may lead to larger SOC swing, over-charging and over-discharging causing the cycle life decline or lower efficiency, it is very significant to estimate SOC accurately to improve power distribution efficiency and usage life [8–10].

A number of SOC estimation methods and techniques have been proposed in recent years, e.g. ampere–hour counting method, artificial neural network, support vector machine technique, Kalman filter-based method and electrochemical impedance spectroscopy method [11]. Ampere–hour counting method is simple and easy to implement, but requires the prior knowledge of initial SOC and suffers from accumulated errors [12]. Estimating the SOC based on artificial neural networks and support vector machine [11,13] can lead to good SOC estimation results with appropriate training data sets. But they require a great number of training samples to train the model. Impedance measurement is an effective technique for SOC estimation [15,16]. In [14], an impedance spectra-based approach to estimate SOC was presented. However, this kind of method requires a set of costly and auxiliary equipments to carry out the impedance measurement that is inconvenient in EVs.

The Kalman filter-based method is generally applied to estimate the SOC online or offline [4,7,11,17–19]. In the research on SOC estimation, both the linear model based and nonlinear model based methods were applied to estimate the SOC. In order to improve the robustness and estimation accuracy, some adaptive Kalman filter estimation methods for SOC estimation were proposed, and the performance was improved. However, these Kalman filter-based SOC estimation algorithms often require accurate parameters of the model, and assume that constant values of the process and measurement noise covariance are known.

Fractional calculus has been applied in various fields, for example, control [20–22,25], signal processing and system modeling [23,24,26,27], and some related researches such as stability analysis of fractional order systems [28]. Recently, fractional calculus was applied in state of charge estimation of battery [12,29,30]. Ref. [12] introduced a fractional calculus method to

* Corresponding authors.
E-mail addresses: zhongqs@uestc.edu.cn (Q. Zhong), zhongfulicn@163.com (F. Zhong).

http://dx.doi.org/10.1016/j.isatra.2016.09.017
0019-0578/

model the constant phase element in the impedance model. Based on the impedance model, a fractional Kalman filter was introduced to estimate the SOC of the lithium-ion battery, and good estimate results were achieved. In Refs. [29,30], fractional order sliding mode observer designed method was employed to estimate the state of charge of lithium-ion batteries based on the presented equivalent circuit model, and the experimental results show that the designed observers were effective and possess good performance.

In the past, sliding mode observer (SMO) has been employed to estimate the SOC for the battery [14,31–33]. The SMO-based SOC estimation method can overcome the drawbacks of the conventional SOC estimation methods like large cumulative errors. It is simple and robust to modeling errors. To do the further research on sliding mode observer for SOC estimation of batteries is significant.

The purpose of this paper is to establish an SOC estimation method for lithium-ion batteries which combines the advantages of SMO with the excellent modeling ability of fractional calculus. Firstly, the fractional calculus is employed to model the battery, and a fractional order RC equivalent circuit model (FORCECM) is set up to characterize the charging and discharging dynamics of the lithium-ion battery. Then, we design fractional order SMOs to estimate the SOC. In order to guarantee the robustness stability and the estimation performance of the designed SMOs, the relevant conditions are derived out. Finally, the experiments are carried out, and the results show that our method is effective.

This paper is organized as follows. In Section 2, the basic definitions, lemmas and theorems are introduced. In Section 3, the fractional order RC equivalent circuit model and the dynamic equations which are employed to describe the dynamics of the battery are presented in detail. Design methodology of the fractional order SMOs for SOC estimation is presented in Section 4. And the results of the test experiment of designed SMOs are shown to verify the performance of the proposed method in Section 5, followed by conclusion in Section 6.

Notations: R^n denotes n-dimensional Euclidean space. $\|\cdot\|$ denotes a 2-norm.

2. Basic definitions, theorems and lemmas

Let us introduce some definitions, lemmas and theorems that will be used in this paper. The Riemann–Liouville definition of α-th order fractional derivative is given by [21,23,34]

$$D_t^\alpha f(t)=\frac{1}{\Gamma(N-\alpha)}\frac{d^N}{dt^N}\int_0^t\frac{f(s)}{(t-s)^{\alpha-N+1}}ds \tag{1}$$

where $f(t)$ is an integrable function, $\Gamma(\cdot)$ is the Gamma function, N is the first integer larger than α ($N-1\le\alpha<N$). The Riemann–Liouville definition of q-th fractional integral is described as

$${}_0I_t^q f(t)=\frac{1}{\Gamma(q)}\int_0^t\frac{f(s)}{(t-s)^{1-q}}ds \tag{2}$$

where $N-1\le q<N$.

Lemma 1 ([35,37,38]). *For a non-autonomous fractional-order system $D^\nu x(t)=f(x,t)$ in which $\nu\in(0,1)$ and $f(x,t)$ satisfies the Lipschitz condition with a Lipschitz constant $k>0$, let $x=0$ be an equilibrium point. When there exists a Lyapunov candidate $E(x(t),t)$ satisfying*

$$\rho\|x\|^\alpha\le E(x(t),t)\le\sigma\|x\|^{\alpha\varrho}, \tag{3}$$

$$D^\nu E(x(t),t)\le-\gamma\|x\|^{\alpha\varrho}, \tag{4}$$

where $\rho,\sigma,\gamma,\alpha,\varrho$ are positive constants, then the equilibrium point is asymptotic stable.

Lemma 2 ([36,35]). *For $\alpha\in C$, $Re(\alpha)>0$, $-\infty<x_1<x_2<+\infty$, and $1\le p\le\infty$, the fractional integral ${}_{x_1}I_t^\alpha f(t)$ is bounded in $L_p(x_1,x_2)$*

$$\|{}_{x_1}I_t^\alpha f(t)\|\le\beta\|f(t)\|, \tag{5}$$

where $\beta=\frac{(x_2-x_1)^{Re(\alpha)}}{Re(\alpha)|\Gamma(\alpha)|}$.

Lemma 3 ([35]). *Consider a fractional-order nonautonomous system $D_t^\nu x(t)=f(x,t)$, where $\nu\in(0,1)$, $f:\Omega\times[0,+\infty]\to R^n$ is piecewise continuous in t, $\Omega\in R^n$ is a closed set that contains the origin $x=0$, the initial value condition is $x(t_0)$. The constant x_0 is an equilibrium point of fractional dynamic system (without loss of generality, let the equilibrium point be 0). Choose a Lyapunov function $E(t)=2x^T(t)x(t)$. According to Leibniz's rule of differentiation, the νth-order time derivative of $E(t)$ can be expressed as $D_t^\nu E(t)=(D_t^\nu x)^Tx+x^T(D_t^\nu x)+2\Psi$, where $\Psi=\sum_{k=1}^\infty\frac{\Gamma(1+\nu)(D_t^kx)^T(D_t^{\nu-k}x)}{\Gamma(1+k)\Gamma(1-k+\nu)}$. Then, there exists a positive constant ψ_1 such that*

$$\left|\sum_{k=1}^\infty\frac{\Gamma(1+\nu)(D_t^kx)^T(D_t^{\nu-k}x)}{\Gamma(1+k)\Gamma(1-k+\nu)}\right|\le\psi_1\|x\|. \tag{6}$$

3. Equivalent circuit model for lithium-ion battery

The charging and discharging process of lithium-ion battery is a complex electrochemistry reaction procedure. In this paper, the fractional calculus is applied to describe the charging and discharging dynamics. A fractional order RC equivalent circuit model for lithium-ion battery is employed, in which a fractional order RC loop is used to model the polarization effect, nonlinear factors, and approximate the modeling errors. Then an SOC estimation method and fractional order equivalent circuit model for the battery are proposed.

The model mainly consists of a capacitance C_p which is used to model the polarization effect, a diffusion resistance R_p, an open circuit voltage (OCV) denoted as V_{oc} which is related to the SOC Z, an ohmic resistance R_t employed to model the ohmic behavior of the battery cell, terminal voltage V_t and instantaneous current. Others are depicted by fractional-order terms. The model used in Ref. [33] employs a capacitance, a resistance and an uncertain term to model the polarization effect. This uncertain term can model the uncertainty of the parameters of a battery. As the electrochemical reaction in the battery is extremely complex, the model in this paper considers the characteristics of the battery further. Not only a resistance, a capacitance and an uncertain term, but also a special term depicted by a fractional order model is applied to model the polarization effect, nonlinear factors, and approximate the errors caused by the model. It is named as fractional-order element (FOE) which aims at improving the model accuracy. The polarization capacitance is in the FOE component. The voltage of the FOE is described as $D_t^{\alpha-1}V_p$ which is in the form of fractional-order integral. When $\alpha=1$, it becomes the common used one, V_p. The diffusion resistance, unknown term ϕ_p and fractional-order element component form a fractional-order RC loop. Symbols ϕ_p and ϕ_v denote uncertainties in the battery. The FORCECM is shown in Fig. 1.

Based on the definition of SOC for lithium-ion battery, the mathematical expression for SOC is given by

$$\begin{aligned}Z(t)&=Z(0)+\int_0^t\frac{I(x)}{C_{ca}}dx\\&=Z(0)+\int_0^t\frac{I_m(x)}{C_{nom}(T)+\Delta C_{nom}(T,t)}dx+\int_0^t\frac{\Delta I(x)}{C_{nom}(T)+\Delta C_{nom}(T,t)}dx\end{aligned}$$