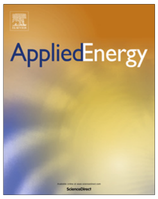
Applied Energy xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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



A novel fractional order model based state-of-charge estimation method for lithium-ion battery

Hao Mu [a], Rui Xiong [a,*], Hongfei Zheng [a], Yuhua Chang [b], Zeyu Chen [c]

[a] Collaborative Innovation Center of Electric Vehicles in Beijing, School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China
[b] Faculty of Automotive and Construction Machinery Engineering, Warsaw University of Technology, Narbutta 84, 02-524 Warsaw, Poland
[c] School of Mechanical Engineering and Automation, Northeastern University, Shenyang 110819, China

HIGHLIGHTS

- A novel fractional order impedance model for lithium-ion battery was proposed.
- The new state-space equations of impedance model was presented.
- Based on the GL definition and short-memory principle, the FOUKF algorithm was inferred.
- The feasibility and robustness of the proposed method were verified under three various cycles.
- The results show that the proposed method can promote the SoC estimation accuracy.

ARTICLE INFO

Article history:
Received 4 May 2017
Received in revised form 5 July 2017
Accepted 8 July 2017
Available online xxxx

Keywords:
Lithium-ion battery
Electrochemical impedance spectroscopy
Battery model
State of charge
Fractional order unscented Kalman filter

ABSTRACT

Accurate state of charge estimation of lithium-ion battery is directly related to the safe operation of electric vehicles and also an indispensable function of the battery management system. Four aspects of efforts are made to improve the estimation accuracy. First, for overcoming the drawbacks of equivalent circuit model and electrochemical model, the fractional order impedance model is built via electrochemical impedance spectroscopy data and the fractional element is used to describe the polarization effect in a simple and meaningful way. Second, the discrete state-space equations of the impedance model are inferred by Grünwald-Letnikov definition and parameters of the model including the order of the fractional element are identified together by genetic algorithm (GA) and the experiment data of the dynamic driving cycles. Third, the fractional order unscented Kalman filter technique is presented and the 'short memory' technique is employed to improve the computation efficiency of fractional operator. Lastly, experimental validation is implemented to verify the effectiveness of the proposed approach and results show that the SoC estimation accuracy can be improved by the proposed model and estimation method. The estimation error can be controlled within the range of 3%.

1. Introduction

Due to the high energy and power density, long cycling and calendar life-time, and low self-discharge rate, lithium-ion batteries (LIBs) have become the predominant choice for electric vehicles [1,2]. Despite those advantages, the practical application has encountered many challenges, such as inconsistency of battery pack, shortcut issues, and heat-runaway. To prevent these problems from happening, reliable states estimation of LIBs, particularly, for the state of charge (SoC), seems rather crucial for battery management systems (BMS). Nevertheless, the sophisticated chemical reactions occur inside the batteries which give rise to the strong nonlinearity and time-varying property of external characteristic, which intensify the difficulty of SoC estimation [3].

In order to tackle this problem, some model-based estimation methods are investigated [4,5]. Among several types of models, the equivalent circuit model is regarded as the most appropriate one for online estimation, and based on this type of model the adaptive filter approaches and many observer techniques are presented to estimate the SoC of the battery effectively [6,7]. Hu et al. [8] proposed the adaptive unscented Kalman filter (AUKF) to estimate the SoC of Lithium Nickel-Manganese-Cobalt Oxide (NMC) battery module based on the zero-state hysteresis battery model.

---

* Corresponding author at: Department of Vehicle Engineering, School of Mechanical Engineering, Beijing Institute of Technology, No. 5 South Zhongguancun Street, Haidian District, Beijing 100081, China.

E-mail address: rxiong@bit.edu.cn (R. Xiong).

http://dx.doi.org/10.1016/j.apenergy.2017.07.003
0306-2619/© 2017 Elsevier Ltd. All rights reserved.

Please cite this article in press as: Mu H et al. A novel fractional order model based state-of-charge estimation method for lithium-ion battery. Appl Energy (2017), http://dx.doi.org/10.1016/j.apenergy.2017.07.003

He et al. [9] also applied the AUKF method to estimate the SoC, but the object was changed to Lithium Iron Phosphate (LFP) battery and the improved combined model was selected which considered the influences of various temperatures and discharging rates. Hu [10] and Xiong et al. [11] successively employed the multi-scale extended Kalman filter to jointly estimate the SoC and capacity of the LIBs on enhanced self-correcting model and Thevenin model, respectively and both of them obtained desirable estimation results. Wei et al. [12] addressed the negative effect of noise contamination on model identification and SOC estimate and the Frisch scheme based bias compensating recursive least squares (FBCRLS) observer was proposed to co-estimate parameters of the enhanced Thevenin model and SoC with high accuracy and robustness. Besides, Zhang et al. [13] used the RC model which is quite different with the ones mentioned above and presented the H_∞ observer to estimate the SoC. However, the lack of physical-chemical explanation for the microscopic movements in the battery is the fatal drawback of this model, and meanwhile the electrochemical model [14,15], which could illustrate the charge transfer between two electrodes and reveal the electrochemical mechanism, is too complicated to be used for online calculation. In recent years, the fractional order impedance model (FOIM) inferred from electrochemical impedance spectroscopy (EIS) has achieved a few of attraction to be investigated. Ref. [16] elaborated the origin of the FOIM, and deduced the fractional order Kalman filter by Grünwald-Letnikov (GL) definition in order to estimate the SoC of the LIB. Ref. [17] specifically expounded the electrochemical mechanism of the EIS variations along with the battery aging and set the Randle model as the baseline to demonstrate the improvements of the presented electrochemistry-based model. Ref. [18] presented a sliding mode observer (SMO) to estimate the SoC of the battery and a self-tuning strategy for the SMO gain was proposed to improve the convergence speed and reduce the high frequency chattering. Refs. [19,20] deduced the inner relationship between traditional ECMs and fractional order ECMs, and used observer technique to estimate the SoC of the battery which acquired satisfactory estimation accuracy and robustness. Ref. [21] presented a simple parameters identification method, namely 'srivcf', which can keep high fitting precision for electrochemical impendence spectroscopy data in frequency-domain. Ref. [22] analyzed the parameters sensitivity of fractional order models and divided these parameters into three categories to distinguish the impacts on the terminal voltages. Ref. [23] systematically compared the fractional order model and ordinary integer order model on modelling technique and SoC estimation, and the advantages of fractional order model were prominent.

Although some work has been done to expand the application of fractional order theory for lithium-ion battery modelling and states estimation, the increased nonlinearity and model complexity due to the fractional calculus cannot be neglected. Therefore, simplified modelling methods and the appropriate estimation techniques, particularly for this kind of strong nonlinear problem, should be focused. This paper is involved to the SoC estimation issue of the lithium-ion battery and some contributions are made as follows: (i) Based on the EIS data and fractional order theory, the fractional order impedance model is established; (ii) The order of the fractional element is identified together with other parameters in the model by GA method using dynamic driving cycles data rather than being identified independently in Refs. [16,19], which could make parameters reflect more comprehensive characteristics of the battery; (iii) Compared with Refs. [16,23], novel state-space functions from the model are inferred by the GL definition and the fractional order unscented Kalman filter (FOUKF) approach is investigated to deal with this nonlinear issue; (iv) Through comparison with the results of traditional ECM calculated by unscented Kalman filter (UKF) method, the feasibility and superiority of proposed approaches are revealed.

The remaining of this paper is organized as follows: In Section 2, some basic knowledge about fractional order theory, electrochemical impedance spectroscopy and impedance model is introduced. Section 3 proposes the fractional order unscented Kalman filter technique to estimate the SoC of the LIB. The validation process is implemented in Section 4. Finally, some conclusions are drawn in Section 5.

2. Fractional order impedance model

In order to conquer the shortcoming of traditional ECMs — the lack of physical-chemical meaning and meanwhile guarantee the optimal trade-off between model complexity and computation efficiency, the impedance model is investigated, based on fractional order and electrochemical impedance spectroscopy theory.

2.1. Fractional calculus

Fractional calculus is a generalization of the traditional calculus and can be traced from the letters of Leibnitz to L' Hospital in 1695. It has been widely used in various fields of science, such as control theory, electric circuits, viscoelasticity, and electrochemistry [24,25]. The continuous integro-differential operator is defined as

$$ {}_aD_t^\alpha = \begin{cases} \frac{d^\alpha}{dt^\alpha}, & \alpha > 0 \\ 1, & \alpha = 0 \\ \int_a^t (d\tau)^\alpha, & \alpha < 0 \end{cases} \tag{1} $$

where α is the order of fractional operator, varying within real number domain, a and t are the bounds of the operation. Three most prevailing definitions of the fractional derivatives and integrals are the Grünwald-Letnikov (GL) definition, the Riemann-Liouville (RL) and the Caputo definitions. The GL definition is inferred from integer-order derivatives and integrals and expresses the unique discrete form of fractional calculus, which is shown as

$$ D_t^\alpha f(t) = \lim_{h \to 0} \frac{1}{h^\alpha} \sum_{j=0}^{\infty} (-1)^j \binom{\alpha}{j} f(t - jh) \tag{2} $$

where the symbol h is the sampling interval and $\binom{\alpha}{j}$ is the binomial coefficients which can be calculated as

$$ \binom{\alpha}{j} = \begin{cases} \frac{\alpha!}{j!(\alpha-j)!} = \frac{\Gamma(\alpha+1)}{\Gamma(k+1)\Gamma(\alpha-j+1)}, & j > 0 \\ 1, & j = 0 \end{cases} \tag{3} $$

where $\Gamma(\bullet)$ is the gamma function. Commonly, in order to implement the fractional derivatives and integrals, it is unavoidable to compute the coefficients $(-1)^j \binom{\alpha}{j}$. One recursive approach has been investigated for simplifying the computation process, shown below [24]

$$ \omega_0^{(\alpha)} = 1, \quad \omega_j^{(\alpha)} = \left(1 - \frac{\alpha+1}{j}\right) \omega_{j-1}^{(\alpha)}, \quad j = 1, 2, 3 \cdots \tag{4} $$

where $\omega_j^{(\alpha)}$ denotes the $(-1)^j \binom{\alpha}{j}$.

2.2. Electrochemical impedance spectroscopy

Electrochemical impedance spectroscopy (EIS) is a powerful technique for separating the electrochemical reactions and tracking the variation of the performance under different state of health (SoH) of the battery in a nondestructive manner [26,27]. Previous

Please cite this article in press as: Mu H et al. A novel fractional order model based state-of-charge estimation method for lithium-ion battery. Appl Energy (2017), http://dx.doi.org/10.1016/j.apenergy.2017.07.003