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An innovative approach for characteristic analysis and state-of-health diagnosis for a Li-ion cell based on the discrete wavelet transform

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HIGHLIGHTS

- The DWT is useful for analyzing signal with non-stationary and transient phenomena.
- The discharging/charging voltage signal (DCVS) is considered as original signal.
- Daubechies dB3 wavelet is used in the multi-resolution analysis (MRA) of the DWT.
- DWT-based MRA is used to extract variable electrochemical information from the DCVS.
- The proposed work shows the clearness for reliable state-of-health (SOH) diagnosis.

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ABSTRACT

This paper introduces an innovative approach to analyze electrochemical characteristics and state-of-health (SOH) diagnosis of a Li-ion cell based on the discrete wavelet transform (DWT). In this approach, the DWT has been applied as a powerful tool in the analysis of the discharging/charging voltage signal (DCVS) with non-stationary and transient phenomena for a Li-ion cell. Specifically, DWT-based multi-resolution analysis (MRA) is used for extracting information on the electrochemical characteristics in both time and frequency domain simultaneously. Through using the MRA with implementation of the wavelet decomposition, the information on the electrochemical characteristics of a Li-ion cell can be extracted from the DCVS over a wide frequency range. Wavelet decomposition based on the selection of the order 3 Daubechies wavelet (dB3) and scale 5 as the best wavelet function and the optimal decomposition scale is implemented. In particular, this present approach develops these investigations one step further by showing low and high frequency components (approximation component A_n and detail component D_n, respectively) extracted from variable Li-ion cells with different electrochemical characteristics caused by aging effect. Experimental results show the clearness of the DWT-based approach for the reliable diagnosis of the SOH for a Li-ion cell.

1. Introduction

As one of the most used batteries in consumer portable electronics in recent decades, Li-ion cells have become more and more favorable choice for portable device, power electronics, and renewable storage applications [1,2]. As a result, in these days, battery management system (BMS) of the rechargeable Li-ion cell is one of the major concerns for electric-powered transportation such as electric vehicles (EVs) and hybrid electric vehicles (HEVs) in order to guarantee the overall system performance. Therefore, for achievement of an improved BMS, accurate and reliable knowledge of a Li-ion cell is crucial to achieve these goals [3–8]. Failure to achieve an improved BMS, leading to over-discharging and over-charging conditions, may cause permanent internal damage [9,10]. However, due to the complex chemical and physical process of the cells, the behavior of the cells show nonlinear characteristic, and thus is difficult to acquire optimal BMS. As a result, in order to overcome these weak points, the electrochemical models [11–16] and the electrical circuit models (ECMs) [17–23] have been representatively studied and applied Li-ion cell for efficient analysis cell's behavior. The electrochemical models enable an utilization of a set of coupled non-

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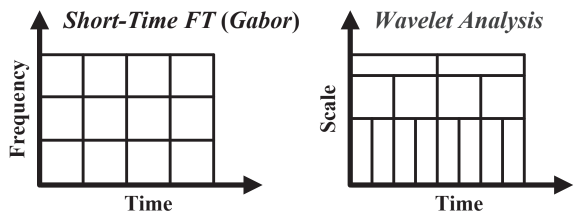

Fig. 1. Windows functions of two signal processing transform.

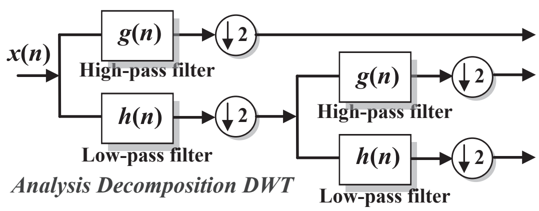

Fig. 2. Discrete wavelet transform (DWT)-based multi-resolution analysis (MRA) of the signal.

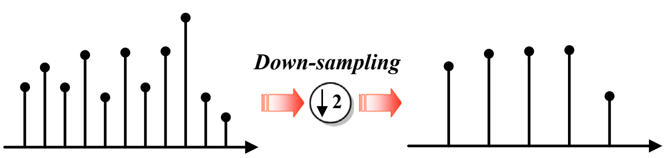

Fig. 3. Down-sampling of the DWT.

linear differential equations for description of the pertinent transport, thermo-dynamic effect, and kinetic phenomena occurring in the cell. In addition to the relationship between microscopic quantities, the distribution in the cell can be easily translated into measureable quantities (cell current and voltage). Unfortunately, the electrochemical models should accompany partial differential equations with numerous unknown parameters, which cause a huge memory requirement and a heavy burden of computation, thus these models are inappropriate to real BMS [24].

The electrical circuit models (ECMs) have been especially investigated for the purpose of BMS and energy management control of EVs and HEVs. These models are generally comprised of resistance-capacitance (RC) networks such as first-, second-, and third-order RC ladders in order to capture *I*–*V* dynamical characteristics of a cell. Through physical parameterization of the ECM, the cell's behavior can be better understood. However, from the model-based state-of-charge (SOC) estimation point of view, it has been observed that difference in electrochemical characteristics due to manufacturing variability and degradation with use, result in wrong parameter values that causes erroneous SOC estimation and low BMS performance. Although the error can be temporarily reduced by repeated measurement of model parameter values, such as exercise would be very inefficient due to time-consuming testing, costly, and labor intensive for obtaining parameter values [24–26]. Therefore, in order to reduce these shortcomings and to enhance battery management with a requirement for more accuracy and representation of the complex nonlinear electrochemical processes, there have been some approaches that deals with parameters variability of model-based SOC and state-of-health (SOH) under different experimental condition [27,28]. The authors in Ref. [27] presented a data-driven SOC and power capability estimation of lithium-ion polymer battery using multi-state joint estimator with different degradation states. The authors in Ref. [28] presented an identical data-driven multi-scale extended Kalman filtering based parameter and state estimation against different battery aging levels. Two references show the clearness for reliable SOC and SOH information with different experimental condition. Unfortunately, so far, little definitive answer has been given to this question. In addition, due to the high complexity and long run-time performance that accompanied by enhance model of sophisticated method such as above references, an heavy embedded microprocessor should be more inevitably required to provide accurate results in real-time battery application, such as real-time SOC estimation and SOH prediction. Besides, it is very time-consuming for design of SOC and SOH estimation algorithms that satisfy the optimum specification. It should be well considered how to evaluate and get a compromise in the balance of complexity and accuracy of the BMS. Therefore, in this overall perspective, without direct an electrochemical or electrical modeling of a Li-ion cell, a novel approach as one of the key technologies of the BMS should be newly discussed in order to minimize aforementioned problems in this work.

This manuscript aims to present a new approach for characteristic analysis of a Li-ion cell based on the discrete wavelet transform (DWT) with focus on minimization of the disadvantages (model-based characteristic analysis). The DWT is becoming a powerful tool for analyzing the discharging/charging voltage signal (DCVS) with a non-stationary and transients phenomena [29–46]. One of its features is multi-resolution analysis (MRA) with a vigorous function of both time and frequency localization. Through DWT-based MRA requiring filtering and down-sampling, the information on the electrochemical characteristic of a Li-ion cell can be extracted from the DCVS over a wide frequency range. During the research specifically developed for this methodology, wavelet decomposition based on the selection of the order 3 Daubechies wavelet (dB3) and scale 3 5 as the best wavelet function and the optimal decomposition scale is used to implement as mother wavelet. The DWT decomposes the DCVS into time and frequency domains and focus on short time intervals for high frequency component (detail; D_n) and on long time intervals for low frequency component (approximation; A_n). Specifically, for feature extraction of the DCVS through DWT-based MRA, approximation A_5 and D_5 components finally decomposed are considered in this work. This study particularly develops these works one step further by showing the values of the standard deviation for high and low frequency components extracted from variable Li-ion cells with

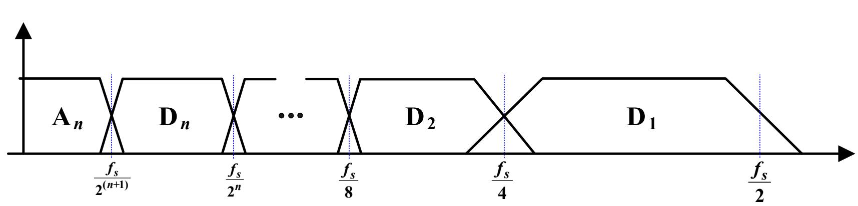

Fig. 4. Frequency bands corresponding to the DWT signal.