Journal of Power Sources 315 (2016) 351–358

Contents lists available at ScienceDirect

Journal of Power Sources

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

Wavelet transformation to determine impedance spectra of lithium-ion rechargeable battery

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HIGHLIGHTS

- Electrochemical impedance was determined by wavelet transformation (WT).
- Theory for the determination of electrochemical impedance by WT was proposed.
- A complex Morlet mother wavelet (CMMW) was used in WT.
- Favorable conditions of variables and constants of CMMW were found.
- Electrochemical impedance of a lithium-ion rechargeable battery was determined by WT.

ARTICLE INFO

Article history:
Received 11 March 2016
Accepted 13 March 2016

Keywords:
Electrochemical impedance
Wavelet transformation
Complex Morlet mother wavelet
Wavelet coefficient
Time domain data
Lithium-ion rechargeable batteries

ABSTRACT

A new analytical method is proposed to determine the electrochemical impedance of lithium-ion rechargeable batteries (LIRB) from time domain data by wavelet transformation (WT). The WT is a waveform analysis method that can transform data in the time domain to the frequency domain while retaining time information. In this transformation, the frequency domain data are obtained by the convolution integral of a mother wavelet and original time domain data. A complex Morlet mother wavelet (CMMW) is used to obtain the complex number data in the frequency domain. The CMMW is expressed by combining a Gaussian function and sinusoidal term. The theory to select a set of suitable conditions for variables and constants related to the CMMW, i.e., band, scale, and time parameters, is established by determining impedance spectra from wavelet coefficients using input voltage to the equivalent circuit and the output current. The impedance spectrum of LIRB determined by WT agrees well with that measured using a frequency response analyzer.

1. Introduction

Electrochemical impedance spectroscopy (EIS) is a powerful tool to evaluate battery performance because time constants in the impedance spectrum can be discriminated without damaging the electrodes. The electrode/solution interface can be characterized by interpreting the electrochemical impedance spectrum because the impedance spectrum in a wide frequency range provides detailed information about the structure of the electrode/solution interfaces. Previously, our group [1–3] employed EIS to investigate the electrochemical properties of the negative and positive electrodes of lithium-ion rechargeable batteries (LIRB) and determined the film resistance originating from the solid electrolyte interphase and charge transfer resistance during the charge–discharge sequence. We reported that the film resistance varied remarkably depending on the kind of additive in the electrolyte solution [1].

An impedance spectrum is typically measured using a frequency response analyzer (FRA), which relies on Fourier transformations of sinusoidal input and output signals. Though it is possible to obtain the impedance spectrum in the wide frequency range using this method, it takes a long time to determine

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http://dx.doi.org/10.1016/j.jpowsour.2016.03.048
0378-7753/

impedance in the low frequency range. To decrease measurement time, fast Fourier transform (FFT) was used to calculate impedance spectrum with time domain measurements [4–15]. With FFT, the time domain data of the system input voltage (current) and output current (voltage) are transformed to frequency domain data. The electrochemical impedance is determined by the cross-spectrum of both input and output data in the frequency domain. Gabrielli et al. [12] determined impedance spectra using FFT with white noise as the input signal. They compared FFT results with those obtained using the FRA for the discussion of measurement time and accuracy. Popkirov et al. [15] calculated impedance spectra of oxidized silver using FFT with various input signals (square wave, random noise, and multi-sine wave). Darowicki et al. [16–18] proposed impedance measurements of a non-stationary model electric system using a pseudo-white noise technique. Ragoisha et al. [19–22] proposed potentiodynamic electrochemical impedance spectroscopy, where a sinusoidal wavelet is superimposed on the terrace of each potential step during a stepwise potential scan.

Takano [23] et al. calculated the impedance spectrum of Li-ion battery by voltage-step chronoamperometry using the Laplace transformation. In this report [23], the finite discrete data for a finite period are recorded and analyzed by the discrete Laplace transform using FFT algorithm. Klotz [14] et al. proposed the technique for fast impedance determination from the time domain data. They [14] used the voltage step as an excitation signal and a discrete Fourier transformation (DFT) with Gaussian window function to determine the impedance of the commercial Li-ion cell. They [14] selected the Gaussian window function to reduce a spectral leakage.

Wavelet transformation (WT) is one of waveform analysis methods for time-dependent signals. Time domain data can be transformed to frequency domain data with WT. Takata et al. [24] proposed a method to calculate the transfer function from time domain data by WT. Their procedure to derive transfer functions in the frequency domain was as follows. First, the time domain input and output signals are transformed to frequency domain signals by a complex Morlet mother wavelet (CMMW). Then, the transfer function is obtained from the ratio of wavelet coefficients of the input and output signals. Later in 2013, Gómez-Luna et al. [25] reported the determination of electric impedance of RLC circuit based on the transient responses. They [25] emphasized the advantage of WT for temporal signals analysis in relation to the Fourier transformation, namely, the finite duration signal can be decomposed by mother wavelet which has suitable time scale though Fourier transformation is essentially decomposition of a sum of periodic complex exponential functions of infinite duration. In the present paper, WT is employed to determine electrochemical impedance of lithium-ion rechargeable battery from time domain data because we can expect very short measurement time for impedance determination. The suitable conditions for data sampling in time domain and convolution integral of mother wavelet and original signals are discussed.

2. Theory

This section describes a theory to support a method that determines electrochemical impedance by WT. The mother wavelet and details of the parameters for WT are explained as follows.

2.1. Wavelet transformation

In WT, the wavelet coefficient $\tilde{f}(a,b)$ is obtained by the convolution integral of a mother wavelet $\Psi(t)$ and original time domain data $f(t)$ as follows.

$$\tilde{f}(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t)\Psi\left(\frac{t-b}{a}\right)dt \qquad (1)$$

Here, a is the scale parameter and b [s] is the time parameter. The wave profile of the Mexican hat mother wavelet $\Psi(t_m)$, which is a most popular mother wavelet, is expressed as follows.

$$\Psi(t_m) = \left(1 - t_m^2\right)\exp\left(-\frac{t_m^2}{2}\right) \qquad (2)$$

In the equation (2), t_m is the time of the mother wavelet, which is obtained by equation (3).

$$t_m = \frac{t-b}{a} \qquad (3)$$

The wave profiles of $\Psi(t_m)$ with different values of a are presented in Fig. 1(a). The $\Psi(t_m)$ in Fig. 1(a) is localized between $t_m = -4$ and 4 s for $a = 1$. For $a = 2$, the $\Psi(t_m)$ is localized between $t_m = -16$ and 16 s. This indicates that the $\Psi(t_m)$ is stretched on the time axis as a increases. The wave profiles of $\Psi(t_m)$ with different values of b are presented in Fig. 1(b). The $\Psi(t_m)$ shifts positively on the time axis as b increases, since b corresponds to the center time of $\Psi(t_m)$. These results indicate that the wave profiles of $\Psi(t_m)$ are

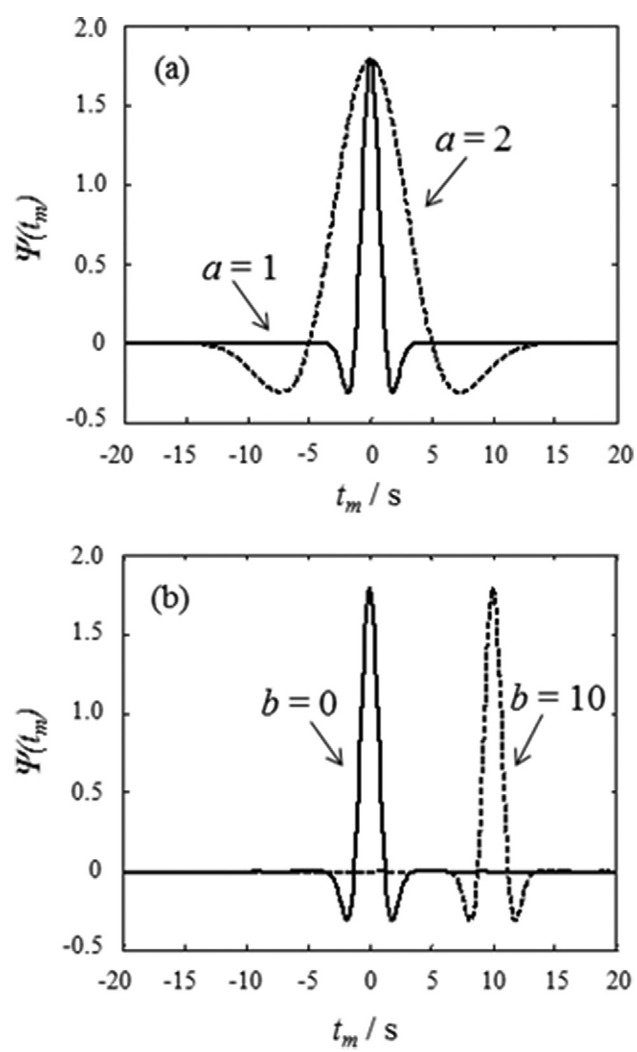

Fig. 1. Wave profiles of Mexican hat mother wavelet with different values of (a) scale parameter a and (b) time parameter b.