Journal of Power Sources 254 (2014) 112–118

Contents lists available at ScienceDirect

Journal of Power Sources

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

Fast measurement of proton exchange membrane fuel cell impedance based on pseudo-random binary sequence perturbation signals and continuous wavelet transform

Andrej Debenjak [a,*], Pavle Boškoski [a], Bojan Musizza [a], Janko Petrovčič [a,b], Đani Juričić [a]

[a] Jožef Stefan Institute, Department of Systems and Control, Jamova cesta 39, 1000 Ljubljana, Slovenia
[b] Centre of Excellence for Low-carbon Technologies — CO NOT, Hajdrihova 19, 1000 Ljubljana, Slovenia

HIGHLIGHTS

- A new approach to the estimation of PEM fuel cell impedance is proposed.
- The approach employees PRBS waveform as perturbation signals.
- The impedance characteristic is computed based on continuous wavelet transform.
- Guidance for optimal parameter selection is presented.
- The impedance characteristic of a PEM fuel cell is obtained in 60 seconds.

ARTICLE INFO

Article history:
Received 29 August 2013
Received in revised form
9 December 2013
Accepted 17 December 2013
Available online 30 December 2013

Keywords:
PEM fuel cell
Impedance characteristic
Electrochemical impedance spectroscopy
Pseudo-random binary sequence
Continuous wavelet transform
Morlet wavelet

ABSTRACT

This paper proposes an approach to the estimation of PEM fuel cell impedance by utilizing pseudo-random binary sequence as a perturbation signal and continuous wavelet transform with Morlet mother wavelet. With the approach, the impedance characteristic in the frequency band from 0.1 Hz to 500 Hz is identified in 60 seconds, approximately five times faster compared to the conventional single-sine approach. The proposed approach was experimentally evaluated on a single PEM fuel cell of a larger fuel cell stack. The quality of the results remains at the same level compared to the single-sine approach.

1. Introduction

Electrochemical Impedance Spectroscopy (EIS) is a widely adopted method for the characterization and diagnostics of Proton Exchange Membrane (PEM) fuel cells. Its use is comprehensively covered in reviews [1–4]. Nowadays, for the purpose of the EIS, the impedance characteristic is measured at a fixed operating point defined by current I_{DC}. To perturb the cells, small-amplitude sinusoidal perturbations with frequencies $\omega \in \Omega$ are applied [5]. Assuming linearity of the fuel cell dynamics around the operating point I_{DC}, the fuel cell responds with sinusoid voltage change with the same frequency ω and particular amplitude and phase. From these signals one can compute the fuel cell impedance at the frequency ω. In order to cover the whole desired frequency range Ω one has to repeat the same procedure multiple of times. Such an approach can be time consuming and in some cases even inappropriate for on-line monitoring of operational fuel cell system. Therefore, to speed up the experiment with minimal intrusion into system's operation, a new time efficient approach for measurement of impedance characteristic is proposed in this paper. The method uses Pseudo-Random Binary Sequence (PRBS) as perturbation signal and the impedance is estimated using continuous wavelet transform (CWT) with Morlet mother wavelet.

With currently adopted single-sine perturbation approach, the impedance plot of a fuel cell is constructed at discrete frequencies. The approach provides precise impedance estimates because all the

* Corresponding author.
E-mail address: andrej.debenjak@ijs.si (A. Debenjak).

0378-7753/$ — see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jpowsour.2013.12.094

energy of the perturbation signal is condensed at one frequency only, as such enabling maximal perturbation at this frequency at the expense of long execution time period of the measurements. Despite the obvious deficiencies, the approach has been employed by the majority of authors. For instance Fouquet et al. [6] used the EIS based methodology to monitor the state-of-health of a PEM fuel cell, estimating the impedance at frequencies ranging from 0.1 Hz to 1 kHz with 10 frequency points per decade. Reportedly, one frequency sweep took approximately 5 minutes to complete. Similarly, Le Canut et al. [7] successfully detected water management faults and catalyst poisoning occurrence by examining the impedance in a higher frequency band from 1 Hz to 10 kHz, where one full measurement sweep took approximately 3 minutes. Long measurement times lead to the problems associated with low-frequency stability and non-linearity of a fuel cell. Additionally, from a practical point of view, such time consuming measurements make this approach inadequate for on-line industrial applications.

Some attempts to reduce the required time of impedance measurement have already been made. Brunetto et al. [8] proposed a multi-sine approach, where the fuel cell under test is perturbed with a signal composed of multiple sinusoids, hence economizing the required measurement time. In the work of Wasterlain et al. [9], the authors clearly exposed the idea of employing multi-sine signals in their further work, even though the single-sine approach was used in the work. In spite of the fact that the multi-sine approach shortens the required time period for the EIS measurements, the approach is not widely adopted. One possible reason might be that time reduction is not significant enough to justify additional complexity of measurement equipment and computation.

Addressing the issues of time consuming measurements and complexity of measurement equipment, this paper presents a novel approach for fast measurement of the PEM fuel cell impedance for the EIS purposes. The proposed approach utilizes PRBS as a perturbation signal. The PRBS is well-established perturbation signal in the field of system identification since it has suitable white-noise-like spectral properties in a predefined frequency band [10]. However, to the best of the authors knowledge PRBS has been neglected for EIS impedance measurements in the context of fuel cell diagnostics. Recently published study by Boghani et al. [11] is the nearest available study to the field of "conventional" fuel cells that uses the PRBS system identification concept. In their study, the PRBS was utilized together with step waveform to analyse performance of a microbial fuel cell by measuring the time constant and steady-state gain of a predefined first order model over the operation range of a cell. In the same manner, Fairweather et al. [12] employed a very low frequency PRBS in order to estimate model parameters of a valve-regulated lead-acid batteries affected by operational temperature. Unlike these studies, the novel approach presented in this paper deals with measuring the impedance characteristic in a frequency band from 0.1 Hz to 500 Hz and it is not limited or predefined by any linear or non-linear model.

The main advantage of the proposed PRBS approach compared to the single-sine and multi-sine ones is a shorter time period required for the measurements. In the case of 0.1 Hz–500 Hz frequency band, the measurements take 60 seconds to complete. The length of measurement time is tightly linked to the lower frequency limit of the frequency band, therefore only slightly higher limit (e.g. 0.5 Hz instead of 0.1 Hz) significantly shortens the required measurement time period. Additionally, as the cell is perturbed by the broadband signal, the value of impedance can be computed at any frequency of interest just with properly adjusted parameters of the computational algorithm.

In the case of sinusoid waveform signals, the Fourier transform is applied to transform the signals into frequency domain [8,13]. However, when using broad-band random signals such as PRBS, it is preferred to perform time-frequency analysis for the impedance computation. One approach is the application of Short-time Fourier transform or wavelet transform. The former one suffers from fixed time-frequency resolution, whereas the latter one allows flexibility in the time–frequency resolution by achieving good time resolution for high-frequency events, and good frequency resolution for low-frequency event. Therefore, in this study CWT approach based on the Morlet mother wavelet was employed for impedance computation. With properly tuned CWT parameters, this approach provides reliable impedance results along the entire frequency band. Additionally, it yields statistical information about confidence interval of the impedance measurement.

The wavelet transform is widely used tool in a variety of scientific fields ranging from diagnostics of human cardiovascular systems [14] and analysis of life signals in mammals [15] to fault detection in mechanical drives [16]. In the field of PEM fuel cell diagnostics, Steiner et al. [17] used discrete wavelet transform to diagnose PEM fuel cell flooding directly from the voltage signals. The flooding was diagnosed based on the pattern of the wavelet packet coefficients derived with the wavelet packet transform.

The paper also addresses the problem of proper parameter selection of both PRBS and CWT with the Morlet wavelet, which has significant influence on the effectiveness of the proposed approach. Special attention is given to the computationally efficient implementation of the algorithms which brings significant practical advantages in implementation of on-line EIS based diagnostic systems. Finally, the paper presents experimental results, where the PRBS approach was applied to a commercial PEM fuel cell system. The PEM fuel cell impedance results acquired using the PRBS approach are thoroughly discussed. The impedance characteristic measured with use of PRBS perturbation signal is compared to the reference impedance characteristic obtained by standard single-sine approach.

2. Pseudo-Random Binary Sequence

According to Ljung [10], PRBS is a periodic and deterministic signal with white-noise-like properties. As such, it is highly appropriate as an input test signal for system identification purposes. The maximum length PRBS can be generated by employing feedback shift registers [18,19]. The maximum length PRBS is characterized by its order n, the maximum length period N, amplitude a and its sampling period Δt. The order n determines the maximum length period N (number of discrete points in time, when the PRBS signal can change its value):

$$N = 2^n - 1 \tag{1}$$

The discrete power spectrum density Φ of maximum length PRBS signal with amplitude a and length N is [19]:

$$\Phi^{d}(m) = \begin{cases} \frac{a^2}{N} & m = 0 \\ \frac{a^2(N+1)}{N} & 0 < m < N \end{cases} \tag{2}$$

Therefore, the power spectrum of periodical PRBS with period N and sampling period Δt is:

$$\Phi^{p}\left(m\frac{2\pi}{N\Delta t}\right) = \frac{1}{N}\Phi^{d}(m)\left|\frac{\sin\frac{m\pi}{N}}{\frac{m\pi}{N}}\right|^2 \tag{3}$$

Fig. 1 resembles the power spectrum of the PRBS signal given by the Equation (3). It can be seen, that the value of the power spectrum hits zero exactly at integer multiples of sampling frequency f_s, which is related to the sampling period Δt as follows: