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Optimal selection of proton exchange membrane fuel cell condition monitoring thresholds

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HIGHLIGHTS

- An analytical method for optimal condition monitoring thresholds is proposed.
- The approach regards the electrical impedance as complex random variable.
- Impedance statistical properties are calculated via Morlet wavelet coefficients.
- Thresholds are determined based on the probability of false alarm.
- Unified and scale-free condition indicator for PEM fuel cells is proposed.

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ABSTRACT

When commissioning or restarting a system after a maintenance action there is a need to properly tune the decision thresholds of the diagnostic system. Too low or too high thresholds may implicate either missed alarms or false alarm rates. This paper suggests an efficient data-driven approach to optimal setting of decision thresholds for a PEM fuel cell system based solely on data acquired from the system in reference state of health (i.e. under fault free operation). The only design parameter is the desired false alarm rate. Technically, the problem reduces to analytically determining the probability distribution of the fuel cell's complex impedance and its particular components. Employing pseudo-random binary sequence perturbation signals, the distribution of the impedance is estimated through the complex wavelet coefficients of the fuel cell voltage and current. The approach is validated on a PEM fuel cell system subjected to various faults.

1. Introduction

Like any other item of equipment the reliability and durability of proton exchange membrane (PEM) fuel cells is affected by faults on various components [1,2]. These faults include corrosion of the electrodes and degradation of membranes [3–6], catalyst and membrane poisoning [7–10], and water management faults (i.e. flooding of gas channels and membrane drying) [11–13]. Timely detection and diagnosis of these faults is of great importance for future employment of PEM fuel cell technology on larger scale [14,15].

Majority of faults that may occur on PEM fuel cells can be detected with multitude of approaches based on electrochemical impedance spectroscopy (EIS) [16–21]. EIS characterization of fuel cell flooding and membrane drying was reported by plethora of authors [22–28]. Portion of these authors used EIS measurement data to directly detect faults [26–28], meanwhile others proposed model based approaches [22–25]. Employing somehow more advanced approach, Kadyk et al. [29,30] proposed a non-linear extension of the EIS diagnostic approach with non-linear frequency response analysis (NFRA) to diagnose fuel cell flooding and membrane dehydration. In addition to the detection of water management faults, Le Canut et al. [27] and Kadyk et al. [31] also tackled detection of anode catalyst poisoning with CO by employing more complex NFRA. All these numerous studies confirm that various PEM fuel cell faults can be observed through EIS impedance measurements. Therefore, an autonomous and effectual condition monitoring system for fuel cells can be implemented by using EIS features.

To the best of the authors' knowledge, at this stage of PEM fuel cell diagnostic's development, using EIS features for condition monitoring requires beforehand EIS characterisation of fuel cell

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behaviour under normal and faulty operation. Having such data, one can set up threshold values that mark the border between fault free and faulty regions.

However, performing such characterisation procedures may be infeasible in many practical situations, since they may lead to irreversible damage of the fuel cell system (e.g. extensive drying and CO poisoning [1,2]). Moreover, due to variation in parameters from one fuel cell to another, once the EIS data is obtained for one particular fuel cell, there is no straightforward way to transfer this particular knowledge to another cell without conducting new complete set of characterisation procedure. Therefore a vital question arises how to design a condition monitoring system employing measurements conducted solely under fault free (normal) operation of a fuel cell.

Implementing an effective condition monitoring system can significantly improve the operation of in-the-field fuel cell power units [32]. Many of the problems for designing an effective condition monitoring system have been addressed in the context of mechanical systems [33,34]. The main difficulty is to determine the statistical properties of the selected features and model their behaviour under faulty conditions [35,36]. Achieving this goal has significant practical importance for any system integrator.

Addressing the issue of beforehand characterisation, this paper proposes a systematic approach for determining the bounds of the fault free region of operation without inducing any faults. In the proposed approach the fuel cell impedance is considered as a complex random variable. The corresponding probability distribution functions are derived, allowing complete statistical characterisation of the behaviour of the complex impedance. As a result, the only design parameter is the desired false alarm rate, which is intuitive and very well understood even by non-specialists in the area of condition monitoring. The effectiveness of the proposed approach was evaluated on a 8.5 kW PEM fuel cell subjected to various water management faults.

The first step towards specifying the fault free region is the analysis of the statistical properties of the feature set as described in Section 2. Using these statistical properties the method for calculating the bounds of the fault free region as well as the overall condition indicator are presented in Section 3. Experimental evaluation of the proposed condition indicator is presented in Section 4.

2. Statistical properties of the fuel cell impedance

Fuel cell electrical impedance is a complex variable that is defined as a frequency domain ratio of the voltage to the current. Regarding the fuel cell system as linear and time invariant one, the electrical impedance can be referred as its transfer function which has a deterministic nature for each frequency. However, when dealing with real world scenarios the observed fuel cell system is influenced by external disturbances, which are generally modelled as stochastic signals [37], as shown in Fig. 1. Since these disturbances are in many cases unmeasurable, their influence is incorporated into the model thus making the mapping between the current and voltage a stochastic one. Therefore, the observed electrical impedance should be treated as a complex random variable.

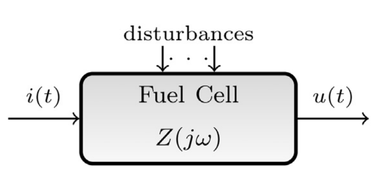

Fig. 1. Representation of fuel cell system excited by current and affected by disturbances.

In order to properly describe the electrical impedance as a complex random variable, the first step is determining its probability distribution function. For that purpose the fuel cell system can be excited using (PRBS) signal [38]. Following the procedure described by Debenjak et al. [38], the impedance characteristic can be efficiently estimated by using the complex wavelet coefficients of the continuous wavelet transform of the fuel cell's current $i(t)$ and voltage $u(t)$ using the Morlet mother wavelet, which is used in a variety of fields [38–41].

2.1. Continuous wavelet transform using the Morlet wavelet

The continuous wavelet transform (CWT) of a square integrable function $f(t)\in\mathbf{L}^2(\mathbb{R})$ is defined as [42]:

$$Wf(s,u) = \langle f(t), \psi_{u,s}(t)\rangle = \int_{-\infty}^{\infty} f(t)\psi^*_{u,s}(t)dt, \tag{1}$$

where $\psi_{u,s}(t)$ is a scaled and translated version of the mother wavelet $\psi(t)$:

$$\psi_{u,s}(t) = \frac{1}{\sqrt{s}}\psi\left(\frac{t-u}{s}\right). \tag{2}$$

The wavelet coefficients (1) describe the analysed signal $f(t)$ on the time-scale plane. The conversion between scale s and frequency f is straightforward and depends on the selection of the mother wavelet (2). Therefore, in the remaining of the paper instead of scale s all subsequent relations will rely on actual frequency f.

For the impedance estimation, one needs information about the instantaneous amplitude and phase of the electrical current $i(t)$ and voltage $u(t)$. Therefore, the Morlet wavelet was chosen as a mother wavelet (2), which reads [43]:

$$\psi(t) = \pi^{-1/4}\left(e^{j\omega_0 t} - e^{-\omega_0^2/2}\right)e^{-t^2/2}, \tag{3}$$

where ω_0 is the ratio between the highest and the second most highest peak and is usually set to $\omega_0 = 5$.

The Morlet wavelet (3) is an analytical function i.e. it has only positive frequencies. As a result, the wavelet coefficients $Wf(t,f)$ in (1) are complex values and at each time translation t and frequency f the wavelet coefficients give the instantaneous amplitude and phase.

2.2. PRBS as excitation signal

PRBS can be regarded as sufficiently close to stationary random noise whose amplitude probability distribution is Gaussian [44]. Analysing such a signal with continuous wavelet transform preserves its statistical properties with in the wavelet coefficients. As a result the complex wavelet coefficients of the measured current $i(t)$ and voltage $u(t)$ for a particular frequency can be regarded as zero-mean Gaussian circular complex random variables:

$$\begin{aligned} Wi(t,f) &= \Re\{Wi(t,f)\} + j\Im\{Wi(t,f)\} \\ Wu(t,f) &= \Re\{Wu(t,f)\} + j\Im\{Wu(t,f)\}, \end{aligned} \tag{4}$$

where $Wi(t,f)$ and $Wu(t,f)$ are the complex wavelet coefficients of the current $i(t)$ and voltage $u(t)$ respectively. Basic definitions about complex circular random variables are given in the Appendix B.

Due to the circularity of the complex random variables as well as the statistical properties of the prbs signal, the complex wavelet coefficients have the following properties: