INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 41 (2016) 13678–13687

Available online at www.sciencedirect.com

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Solid oxide fuel cell fault diagnosis and ageing estimation based on wavelet transform approach

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ARTICLE INFO

Article history:
Received 4 March 2016
Received in revised form
16 May 2016
Accepted 13 June 2016
Available online 12 July 2016

Keywords:
Solid oxide fuel cell
Fault diagnosis
Wavelet transform
Energy content
Entropy

ABSTRACT

The paper aims at developing a signal-based diagnosis tool diagnosing a high temperature fuel cell named solid oxide fuel cell (SOFC). The wavelet transform (WT) has been used to decompose the SOFCs voltage signals and to find out the effective feature variables that are discriminative for distinguishing the normal and abnormal operating conditions of the system. The diagnosis method is used to detect and isolate SOFC system fault by using the fuel cell stack as a sensor. Considering this, on-line fault detection without any additional sensor is available.

Introduction

Nowadays, the hydrogen encountered a great interest as a fuel, and more efforts are done by industry and governmental institutions to develop hydrogen-based devices [1,2]. Hydrogen is the most abounding chemical element in the universe. On Earth, hydrogen does not exist in a natural state but is very plentiful in the form of atom. This atom has to be extracted from his combination with other atoms (like in water: H_2O) by the mobilization of a source of energy. Nevertheless, the International Energy Agency underlines in Ref. [3] that the main hydrogen source is hydrocarbon reforming [4], even if it can be obtained through green energy procedures. Solid oxide fuel cells (SOFC) [5–9] represent an emerging technology for clean, reliable, and flexible power production [10]. High temperature fuel cells convert chemical energy of fossil fuel into electrical energy [11]. Thus, they are highly efficient and imply low carbon dioxide emission energy conversion devices [12–14]. Compared to other fuel cell

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http://dx.doi.org/10.1016/j.ijhydene.2016.06.143

technologies, the main advantages of the SOFCs are the wide range of applications and the flexibility of fuel tolerated [15,16], also when pure hydrogen derived from renewable energies is used, there is no pollution of environment [17,18]. In Ref. [19], another effective solution to environmental and efficiency issues are to couple the SOFC with a conventional gas turbine: this hybrid system allows reducing pollutants emissions [20] and allows cogeneration applications by exhausting gases at desired temperature [21,22]. Nevertheless, the big issue is that SOFCs have not reached commercialization yet and are still an expensive technology. Moreover, theoretically, fuel cells should produce electrical energy as long as they are fed with gases. Unfortunately, it is not the case because of potential failures on the system, and intensive research studies about diagnosis method in order to increase the lifetime by limiting the performance degradation are being conducted. In Ref. [23], Tu et al. present some ageing mechanisms and lifetime in solid oxide fuel cells. They identify some kinetics and operating conditions that contribute to address lifetime limitation. Thus, the field of system diagnosis is more studied. Diagnosis tools are essential to avoid premature degradation of the fuel cell. The main task of fault diagnosis is to evaluate the deviation of the current state from the normal behaviour of the fuel cell, by detecting the hazardous states. The SoH has to be identified by diagnosing these faulty modes. To reach this goal, several stages have to be followed as: data acquisition, data treatment and fault detection. Firstly, datasets must be collected from the system, operated under different operating modes (healthy and faulty modes). Data treatment aims at extracting and selecting features that enable characterizing the behaviour of the FC [24]. Two main approaches of fault diagnosis have been developed: model-based method [25–27] and signal-based approach [28–30]. A review on diagnosis methodology and technique for SOFC is given in Ref. [31]. Two reviews on modelling listed the different fault detection methods: Andersson et al. [32] present the modelling development for multiscale chemical reactions coupled transport phenomena in SOFC whereas Zabihian et al. [33] review the modelling of hybrid SOFC systems. In Ref. [34], a method is developed in order to estimate dynamically the temperature inside the 10 kW-SOFC by using a data-based modelling. For the model-based approach, a large amount of data is required in order to increase the precision of the diagnosis. In Refs. [35,36], the wavelet-based method is used for on-board energy management for a hybrid vehicle. In these works, the diagnosis method consists in implementing sensors in a system in order to detect parameters deviations from nominal operating conditions. As the fuel cell system complexity increases, another way to achieve diagnosis is to analyze and use the system responses to a solicitation signal as a state of health (SoH) indicator, with the aim to use only already available measurements on the system. The signal-based method using wavelet transform allows reducing the requirement of experimental data which induced saving time and money. Diagnosis procedure will be therefore carried out using either the stack or the complete system as its own sensor [37]. A focus is done on the stack voltage signal. The stack voltage is analyzed with the chosen diagnosis tool (i.e. WT). Without database and relevant information about the faulty and healthy modes and knowledge about the FC system behaviours, fault diagnosis cannot be achieved. In this paper, a signal-based approach is chosen. The WT is a method for signal decomposition but it is not sufficient to diagnose the fuel cell system state. Regardless of the approach, the aim is to generate indicators that distinguish the normal and abnormal SoH. Three indicators extracted from the fuel cell signal are exposed. They allow performing a fast fault diagnosis result as patented in Ref. [38]. Thus, the WT approach is coupled with the analysis of some indicators like the wavelet energy and the wavelet entropy, which gives interesting results. The stack experiments including two different short stacks are described in the third section. The datasets obtained are used to provide some results for fault diagnosis and also for the estimation of the state of health of the fuel cell while performing long-term test. The fault diagnosis algorithm performances are given in the last part of the paper according to the indicator (energy of entropy) and also depending on the stack studied.

Signal-based method

The method is based on the wavelet transform (WT) of the stack voltage signals extracted from different kinds of tests coming from two different SOFCs (presented on the following Section Application to fuel cell). The WT is one of the most popular candidates of the time–frequency transformations [39–42] (that implies extracting time and frequency information from the input signal studied). The continuous WT is defined by Eq. (1).

$$C(u,s) = \frac{1}{\sqrt{s}} \int f(t) \cdot \Psi * \left(\frac{t-u}{s}\right) dt \tag{1}$$

where $f(t)$ is the original signal, $C(u,s)$ is the transformed signal, u is the translation parameter and s the scale parameter. The translation parameter corresponds to the time information in the transformed domain whereas the scale parameter is proportional to $1/signal_{frequency}$. A larger scale denotes a dilated wavelet and a smaller scale denotes a compressed wavelet as presented in Fig. 1.

The WT acts like a filter which splits the high frequency and the low frequency contents. The filtering process is given on Fig. 2. The input signal is downsampled and results in two subsignals. The approximation subsignal denotes the low frequency or high scale of the input signal whereas the high frequency is illustrated by the detail or small scale of the input signal. In the case of multi-level decomposition of the initial signal f, the behaviour described on Fig. 2 is repeated. The approximation is successively decomposed in two subsignals: one detail and one approximation. According to the principle

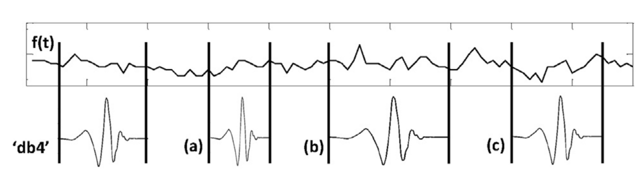

Fig. 1 – (a) Compressed scale, (b) Dilated scale, (c) Translation of the initial Daubechies wavelet called "db4".