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High Fuel Utilization in Solid Oxide Fuel Cells: Experimental Characterization and Data Analysis with Continuous Wavelet Transform

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HIGHLIGHTS

- High Fuel Utilization in SOFCs was studied experimentally and numerically.
- An experimental procedure was developed to characterize SOFC under high fuel utilization.
- A micro-CHP system was characterized with the mentioned test procedure.
- Continuous Wavelet Transform was applied to the voltage to develop a diagnostic tool.
- Signatures were found for different fuel utilization levels.

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ABSTRACT

The on-line diagnostics of Solid Oxide Fuel Cells (SOFCs) is a critical tool to achieve optimal performance and extend the lifetime. The Continuous Wavelet Transform (CWT) methodology was applied to the SOFC voltage signal to detect signatures that reveal the presence of a fault in the cell/stack. The selected fault was anode re-oxidation caused by high Fuel Utilization (FU) (higher then nominal). To experimentally emulate the high FU faults, a standard test procedure was developed, which was used to characterize a μ-CHP system at high FU operation. To complete the analysis, data collected on Single Cells were exploited too. The CWT was applied to the voltage signal for each FU level to verify the qualitative difference (signature) between the signals at different FU's within the same tests as well as the correspondence between the same conditions over different tests. A statistical study was performed to quantify the observed differences and to determine the correspondence between CWT coefficients and operating conditions. The approach proves to be suitable to diagnose high FU in SOFC, showing a successful detection rate above 76%. The results show the good potential of using the CWT methodology as diagnostic tools for SOFCs from cell to stack level.

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1. Introduction

The Solid Oxide Fuel Cell (SOFC) technology is nowadays widely recognized as a promising alternative solution for Auxiliary Power Units (APUs) and Combined Heat and Power (CHP) systems, to meet the targets of higher efficiency and lower carbon dioxide emissions [1]. Although many achievements, such as high efficiency, fuel flexibility, and low emissions show the benefits of this technology, crucial bottlenecks, such as low durability and reliability, still need to be overcome.

Reliability targets have been set in the USA, European Union (EU) and Japan. For instance, the EU commission has set the target of 5000 h lifetime for transportation applications, which is the minimum requirement for vehicles in practical use; while the target for stationary applications has been set to 40.000 h of operation.

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To meet the target of reliability and lifetime, it is necessary to develop adequate diagnostic tools able to detect and identify different types of performance losses. However, no diagnostic tool can be properly developed without a full understanding of the degradation mechanisms as well as a good knowledge of the related parameters and their interactions.

The optimal operation of an SOFC requires a careful choice of the operating conditions, due to the complex processes of this technology. Inappropriate operating conditions hinder optimal performance and lead to severe dysfunctions. The type of fault or failure that can occur are classified as chemical or mechanical. Examples of chemical degradations are carbon deposition, chromium poisoning and interconnects corrosion. Operating SOFCs at oxygen-to-carbon ratios lower than prescribed leads to carbon deposition, resulting in reaction site obstruction. The latter is a major cause of performance loss since the active area available for electrochemical reactions is reduced. Nickel sintering and coke formation in the anode not only results in a loss of the active surface, but also in a change of the porosity, altering the gas transport properties. The cathode side can experience chromium poisoning due to the chromium evaporated from the interconnects [2,3]. The cells of an SOFC stack are electrically connected through metal alloys interconnects, whose degradation is linked to the metal behavior under high temperature conditions, i.e. oxidation and/or corrosion, resulting in increased electrical resistance. Batfalsky et al. [4] reported a chemical interaction between the glass-ceramic sealants containing Lead Oxide (PbO) and the interconnect steels in SOFC stacks. This interaction results in oxide nodules and causes local short-circuiting between individual stack planes. On the other hand, both SOFC electrodes are subject to mechanical degradations, such as crack or delamination when high thermal gradients are present. These degradations cause microstructural changes, a loss in the active surface and activation losses augmentation [3].

Furthermore, besides the faults linked to the material corrosion and stress, there are other important causes of degradation. For instance, it is a common practice to operate SOFCs with excess air and fuel. While supplying excess fuel is necessary to avoid anode oxidation, since the oxygen partial pressure increases by converting the fuel into steam, this excess fuel should be limited to reach a higher electrical efficiency. The fuel utilization (FU), defined as the ratio between consumed and supplied fuel, is indeed an important parameter. The FU should be set carefully since it influences the fragile equilibrium between a high electrical efficiency and a degradation linked to anode oxidation [5].

In the last decades, great effort has been made to create tools that allow to understand these degradation mechanisms and identifying their occurrence. Three diagnostic approaches can be used: model-based, expertise-based and signal-based methodology. The first type of approach relies on a physical model of the fuel cell. The residuals, generated comparing the model outputs and the measured values, are analyzed to detect and identify the occurrence of a fault. The most used model-based diagnostic approaches are based on Electrochemical Impedance Spectroscopy (EIS) measurements analyzed through Equivalent Circuit Modeling (ECM), which proves to be a reliable tool for SOFC diagnosis [6,7]. Onanena et al. [8] succeeded in predicting the lifetime of a PEM fuel cell by extracting features from EIS data. The expertise-based approaches rely on the gained knowledge, the past experience and accumulated expertise. Fault tree analysis (FTA) is one of the tools that links faults to characteristic symptoms via a “top-down” approach, generating signature matrices [3,9]. The signal-based approaches are carried out by processing some specific signals coming from the system. These approaches are widely used for PEMFCs because of the on-line applicability (thanks to the low computational burden) and because they do not require the installation of expensive sensoring equipment. Among the different signal-based approaches, the analysis of the cells output voltage signal (OVS) with the wavelet transform (WT) technique is emerging as one of the most suitable. While the Fourier Transform (FT) used in the EIS technique transposes the signal to the frequency domain, the WT methodology decomposes the OVS in both frequency and time domain, allowing to recognize the occurrence of different electrochemical phenomena without losing the important time-dependence of the voltage signal. The open literature contains a few examples of applications where this approach has already been employed, such as for Li-ion batteries and PEMFCs diagnostics. Kim et al. [10,11], applied the Discrete Wavelet Transform (DWT) decomposition of OVS to both Li-ion batteries and PEMFCs. They analyzed the OVS cell by cell to diagnose the State of Health (SoH) of different cells. Steiner et al. [12–15], developed a diagnostic tool based on the OVS analysis with a DWT algorithm to discriminate between PEM fuel cell flooding and non-flooding operation. The required information is extracted exclusively from the raw fuel cell voltage. As the latter is a standard measurement in all fuel cell applications, no diagnostics-dedicated sensors or apparatus are needed, which makes the implementation of the method more effective. In the case of signal-based approach, the necessary detecting equipment has to be minimized, because additional instrumentation is a possible source of errors and causes increasing system cost and volume.

Analyzing the limited available literature, it is evident that the WT methodology is a relatively new technique in the field of fuel cells and suffers from a lack of demonstrated practical applications. However, this novel approach is very promising as it entails minimum computational effort, does not require tedious modeling, does not need additional expensive sensoring systems, and at the same time guarantees high accuracy and reliable diagnosis. For instance, the EIS methodology, although powerful and versatile, requires the use of suitable instrumentation to generate current/voltage sinusoidal stimuli, and to acquire the corresponding voltage/current response. This can result in a significantly increase of the fuel cell system cost and complexity. It is also important to remark that diagnostic tools developed with the EIS methodology are model-based (e.g. ECM) approaches, whereas the diagnostic tools developed with the WT methodology are purely signal-based approaches. This means that the parameters used for the diagnostics with WT are directly extracted from the signal analysis, with no need for a model. On the other hand, the EIS model-based approaches employ different parameters depending on the specific model used. Furthermore, the model parameters can be identified with various identification techniques. Consequently, the comparison between the outcomes of the EIS and the WT diagnostic approaches is not as straightforward as it might appear.

This study presents the development of a methodology to test an SOFC in faulty conditions and the related signal-based diagnostic tool. Specifically, the selected fault is anode re-oxidation induced by high local fuel utilization (FU). The term high FU is used to indicate a FU value higher than the one prescribed by the manufacturer (nominal FU). An ad-hoc test protocol is defined to gradually increase the FU and ensure stable and sustainable operating conditions, which can be compared with the reference status (nominal condition). The Continuous Wavelet Transform (CWT) is used to extract periodic features of the recorded voltage signal. The outcome of the CWT is a map of coefficients that are analyzed to find a correlation with the State of Health of the SOFC. This diagnostic technique can be potentially applied to any SOFC system with minimal hardware costs. The only signal to be acquired is the stack and cell (or clusters) voltage at a frequency of at least 1 Hz, which is usually already available on most SOFC commercial systems.

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