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Proton exchange membrane fuel cell failure mode early diagnosis with wavelet analysis of electrochemical noise

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ABSTRACT

A diagnostic method for the performance degradation of low temperature proton exchange membrane fuel cells is proposed. The method is based on the analysis of the cell electrochemical noise. Experimental noise data were collected for a range of air relative humidities and stoichiometries including conditions leading to water flooding, membrane dehydration and air starvation failure modes. Data were converted with a Fourier transform (frequency window averaging of the amplitude) and a wavelet transform (coefficients standard deviation). Data were compared to impedance spectroscopy results. The method based on the wavelet transform was more sensitive. Cell states labeled by their air relative humidity and stoichiometry were correctly identified using a brute force algorithm by minimizing the Chebyshev distance between the actual and the calculated states. Independent and uniformly distributed random variations were added to experimental wavelet coefficients' standard deviations to define the calculated states.

Introduction

Proton exchange membrane fuel cells (PEMFCs) are considered as an option to power a range of devices due to advantages, such as high efficiency, quiet operation and environmental friendliness, if fed with hydrogen generated from solar energy. These devices are subject to failure modes requiring diagnostic equipment for identification. Flooding of flow field channels by liquid water has been studied using transparent fuel cell designs [1]. Local fuel starvation is detected by segmented cell designs for current and voltage distributions [2]. However, these methods are invasive and affect the system being measured. The transparent fuel cell wall is a thermal insulator as opposed to the heat conductive carbon bipolar plate [1]. A significant change in surface properties is also introduced, which affects water management. As for segmented cell measurements, the insulator separating the segments translates into a decrease in the active area for electronic conduction through the bipolar plate. Furthermore, the use of shunt resistors to measure the current distribution induces changes absent during normal fuel cell operation [3]. As a result, efforts have been devoted to the development of less invasive measurement methods, such as neutron imaging to measure the water distribution [1] and magnetic field sensors external to the fuel cell to measure current

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distributions [4]. However, these methods still require significant equipment and expenses that cannot be incorporated into actual fuel cell system operations.

A more elegant, non-invasive approach is available by listening to the electrochemical device, recording and analyzing the noise generated. Such an approach has been investigated for corrosion processes [5–7], batteries [8–10] and coatings [11–13]. Only a few reports discuss applications to fuel cells [14–17]. However, in the first report, the electrochemical noise was monitored with a biofuel cell [14], which is not relevant to the present PEMFC discussion. In other studies, only a single failure mode is considered [15,16] by varying the relative humidity of the reactant streams. This is an unrealistic situation for the commercial introduction of fuel cells as several failure modes were identified. As for the last report, the authors proposed 5 different methodologies to analyze fuel cell noise [17]. However, the proposed methods were not applied to fuel cell data, and therefore, their effectiveness is unknown. More recent efforts have focused on the use of the wavelet transform and calculated wavelet coefficients [18–21]. However, the full potential of this approach has not been fully explored in view of the number of diagnostic parameters that can be derived from the wavelet coefficients (for instance the average, standard deviation and total energy).

Other approaches based on noise measurements have been proposed. Acoustic emissions generated during material deformation were demonstrated for membrane dehydration [22,23]. Fuel cell impedance noise at low frequencies was correlated with water drop formation [24]. Magnetic field noise surrounding a fuel cell during operation was linked to flow field channel flooding, membrane pinholes and hydrogen contaminated with acetone [25]. All of these examples suffer from at least one of the following issues: the noise is induced with the use of an excitation signal (impedance measurements), methods need to be ascertained for fuel cell failure modes other than those originally considered, equipment that is not expected to be part of a fuel cell system is needed, or a clear distinction between different failure modes (unique signatures) was not proven. Two noise amplification techniques were also suggested: superimposed pressure oscillations [26,27] and pseudo-random binary sequences in the current [28]. However, in both cases, additional equipment is required, which negatively impacts system simplification for reduced cost and improved robustness.

The development of an early detection and identification strategy for PEMFC failure modes during operation is the focus of the present study. The fuel cell voltage noise is collected and analyzed because the fuel cell system is expected to include electrical variable measurement equipment, such as a cell voltage monitoring system [29]. The air stoichiometry and relative humidity were varied to emphasize ionomer dehydration, flooding and starvation failure modes. Fourier and wavelet transform analyses of the measured noise and electrochemical impedance spectroscopy (EIS) data were compared to determine the best strategy in terms of sensitivity, real time analysis and existence of unique signatures. Wavelet transform (WT) and short-time Fourier transform (STFT) were suited for failure detection and diagnosis in real time. These two methods are compared in Refs. [30,31]. It was concluded that STFT provides faster signal processing, but WT provides a higher-quality analysis at the expense of a greater computational cost. It is emphasized that the noise analyses were completed off-line in this report to demonstrate feasibility. The real-time implementation of the method for an enlarged set of failure modes is left to a subsequent report.

Experimental

Fuel cell and test station

The experimental work was performed at the Hawaii Sustainable Energy Research Facility (HiSERF) at the Hawaii Natural Energy Institute. Fuel Cell Technologies 50 cm^2 single cell hardware with a double serpentine anode and triple serpentine cathode flow fields were utilized. Membrane/electrode assemblies (MEA) were produced by General Motors Research and consisted of a Dupont Nafion NRE211 membrane and electrodes with 0.05 and 0.4 mg cm^{-2} platinum loadings on the anode and cathode, respectively, using Vulcan carbon as the support. The electrode ionomer was Dupont Nafion perfluorosulfonic acid dispersion D2020, and the diffusion media utilized was MRC105 from 3M. Virgin PTFE gaskets were used for sealing and as shims to achieve ~ 20% compression of the diffusion media.

All experiments were conducted using a fuel cell test station originally constructed by UTC Power (formerly International Fuel Cells). The station uses two National Instruments SCXI data acquisition chassis, a LabVIEW based GUI developed in-house and a scripting system for station control. The fuel cell was operating in counter-flow mode with the cell temperature control in the cathode flow field (end plate cartridge heaters). The gases were humidified using an Arbin DPHS-D10 humidifier with heated gas transfer lines. The cell pressure was controlled at the outlet of the fuel cell.

Test conditions and sequence

For all experiments, several cell operating conditions were held constant while varying the cathode stoichiometric air flow and the cathode humidification levels, i.e., air/H^2, 80 °C cell temperature, 150 kPa absolute outlet pressure, 1.5 anode stoichiometric hydrogen flows, 75% anode relative humidity, and 800 mA cm^{-2} current density. Two separate experimental sequences varying the cathode relative humidity and stoichiometry were used during the noise measurements. In the first experimental sequence, the cathode stoichiometry was swept and the values of the cathode relative humidity were fixed. The cathode stoichiometry was varied from 2 down to 0.9 using steps of 0.1. The fixed relative humidity values were 50, 75, 100, and 125%. As the humidifier reaches steady state much sooner when changing the flow as opposed to changing the dew-point temperature, each step during the stoichiometry sweep was held to 300 s. For the second experimental sequence, the cathode relative humidity was swept while the cathode stoichiometry was fixed. The values of the relative humidity were varied between 50 and 130% using steps of 10%. The fixed value of the stoichiometry was varied from 2 to 1.2 using steps of 0.2. As the humidifier takes longer to stabilize