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Online health monitoring of a fuel cell using total harmonic distortion analysis

Sobi Thomas [a], Sang C. Lee [a,*], A.K. Sahu [b], Sam Park [c,**]

[a] Wellness Convergence Research Center, DGIST, 50-1 Sang-Ri, Hyeongpung-Myeon, Dalseong-Gun, Daegu 711-873, Republic of Korea
[b] Energy Systems Engineering, DGIST, 50-1 Sang-Ri, Hyeongpung-Myeon, Dalseong-Gun, Daegu 711-873, Republic of Korea
[c] Department of Mechanical Engineering, University of Louisville, KY 40292, USA

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ABSTRACT

The present work aims to show the nonlinear behavior of a PEM fuel cell under different mass transport conditions. Understanding this behavior helps in online state-of-health monitoring and control of a fuel cell stack. To analyze the health of an operating stack, a total harmonic distortion analysis (THDA) system requires only the sum of voltages or currents of the stack to be monitored. A low-frequency current or voltage signal is impressed on the fuel cell stack, and the resulting voltage or current signal is measured. To determine any change in harmonics, the measured signal is processed with a harmonic analyzer. The operational states of individual cells of the fuel cell stack may be inferred from at least one change in the harmonic content of the impressed signal. The mass transport problem related to the cathode and anode is distinguished using mixed-frequency signals. The present study found experimentally that hydrogen starvation is dominantly observed in the harmonic analysis only below a frequency of 15 Hz, whereas air starvation showed harmonic changes at frequencies below 100 Hz. Total harmonic distortions were observed to rise to 2–2.5% under both the starvation conditions but with different frequency signals.

1. Introduction

The requirement for an efficient and sustainable new energy source is one of the biggest environmental challenges for humankind, especially in the context of steeply rising energy consumption [1–3]. Consequently, the field of renewable energy has become a technology of great interest. The automobile industry is one of the biggest energy consumers, thanks to the preponderance of car fleets. This increasing demand for energy, coupled with concerns about greenhouse gas emissions, has spurred research into alternative fuels and technologies for automotive applications. With the highest energy content per unit mass of 120 MJ/kg, hydrogen is proving to be a promising alternative for clean energy generation. Hydrogen fuel cell (FC) vehicles have the potential for lower emissions than current internal combustion engine vehicles and can offer higher energy density than existing battery-based electrical vehicles [4].

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[*] *Corresponding author*. Tel.: +82 53 785 4730; fax: +82 53 785 1209.
[**] *Corresponding author*. Tel.: +1 502 852 7786; fax: +1 502 852 6053.
E-mail addresses: sclee@dgist.ac.kr (S.C. Lee), Sam.Park@louisville.edu (S. Park).

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While the typical net operating effciency of a fuel cell system slightly exceeds 40%, a combined heat and power installation that utilizes the waste heat of a fuel cell can deliver 80% effciency or higher [1,2]. Polymer electrolyte membrane (PEM) fuel cells are being considered in the automobile industry as a potential replacement for existing power sources, because of their low cost of maintenance, high effciency, quick start-up, and modular nature [5]. PEM fuel cells are classified into low-temperature polymer electrolyte membranes (LTPEM) and high-temperature polymer electrolyte membranes (HTPEM). Though LTPEM fuel cells have various advantages, carbon monoxide (CO) tolerance with LTPEM is a critical issue that HTPEM is able to solve [6–10]. Li et al. showed the influence of temperature on CO poisoning. They reported a CO tolerance of 3% at a 200 °C up to a current density of 0.8 A/cm^2 while at 80 °C the allowable CO content without much degradation is found to be 25 ppm in the fuel [6]. The performance studies at high temperature and low humidity were carried out and it was reported that the higher temperature leads to a lower CO poisoning which allows a reformed gas supply to HTPEM [7,8]. In another study the voltage loss at different temperature with varying CO concentration in the fuel was studied. HTPEM fuel cell showed a high tolerance to voltage loss with CO content of 2–5% in the fuel at 180–200 °C [9,10]. In HTPEM, a polybenzimidazole (PBI) membrane doped with phosphoric acid operating optimally at 160–180 °C is incorporated, instead of a Nafion® membrane, widely used by LTPEM fuel cells [11]. Because of high temperatures, the HTPEM fuel cell system is able to tolerate CO content in fuel of up to 1% with marginal variation in performance. This is what makes HTPEM fuel cells very attractive, as low-quality reformed hydrogen can be used. Another advantage is that water management problems are avoided, as phosphoric acid serves as the proton carrier. This also leads to lower fuel reforming costs, and, as a result, overall system costs are reduced [12–14].

From the research and development point of view, significant emphasis has been placed on the development of durable PBI-based membranes and HTPEM fuel cell systems based on PBI membranes [15–18]. However, although HTPEM fuel cell systems of various types have been developed recently, a number of technical and economic issues still prevent the widespread implementation of these FCs in automobiles. To ensure the smooth operation of a fuel cell system, it is imperative to have a monitoring system to assess the operational state of a fuel cell stack comprising multiple cells connected in series, in order to maintain proper control over the stack so that it can serve as a durable power source. The series connection of several cells in a stack carries the danger that faulty operation of even a single cell can cause the failure of the whole stack and thus shorten the lifetime or reduce the reliability of the system. In a fuel cell stack, it is necessary to maintain the voltage of each individual cell above a threshold level, in order to ensure a higher durability and also proper functioning of the power pack with less maintenance. The most common method used to characterize the electrochemical performance of the fuel cell system is examination of the current–voltage curves, because this method is easier to implement than any other electrochemical technique, such as AC impedance and the current interruption method [19,20]. However, the online monitoring and control of a fuel cell system are still an issue.

Presently, two methods are used for diagnosing the state of health of a fuel cell stack, namely cell voltage monitoring (CVM) and electrochemical impedance spectroscopy (EIS). The CVM system is an online process that requires complex wiring to measure multiple voltages. The CVM method cannot be used to detect the cause of a failure. Electrochemical impedance spectroscopy is a process generally used in offline mode. The advantage of the impedance method is that it can be used to identify the cause of failure, but it requires complex monitoring and computation [21]. Though the aforementioned diagnostic tools can detect the failure of the stack, they involve high cost. Thus, it is imperative to develop an online monitoring and control system for fuel cell stacks with minimum complexity and cost.

Ramschak et al. first introduced the method of total harmonic distortion analysis (THDA), which is a well-known diagnostic tool in electrical engineering [22,23]. In this technique, the failure of even a single cell in a stack can be detected with a minimally complex wiring system, as it requires the measurement of only the stack voltage and stack current, thus facilitating the online diagnosis of the stack. Reducing the cost of a monitoring system for fuel cell stack is a vital step toward the implementation of a widespread fuel cell system. Ramschak et al. verified the THDA methodology for a 1-kW PEMFC stack as well as with a 50 cell SOFC stack. They demonstrated the potential of THDA for starvation condition in a stack [22]. Similar attempts to characterize the electrochemical phenomena of direct methanol fuel cells (DMFC) were carried out by Mao et al. [24,25]. They illustrated the nonlinear behavior of an anode compartment and also the relationship between methanol and the harmonic contents using THDA. In a more recent work, Mao et al. [26] revealed the potential of THDA in the characterization of the oxygen reduction reaction (ORR) at certain kinetically controlled frequency ranges. Although THDA has been proposed as a potential diagnostic tool, significantly more work has to be done to distinguish various phenomena in a fuel cell stack for proper controller design and implementation. The main contributions of this article are as follows:

- The frequency range for air starvation as well as hydrogen starvation is experimentally determined.
- An analysis of the problems associated with a fuel cell stack, namely oxidant starvation and fuel starvation of a single cell, is successfully presented.
- Total harmonic distortion at different frequency levels is experimentally demonstrated.
- The different frequency dependence of anode- and cathode-side critical issues is studied.

This manuscript first surveys prior monitoring and control methods, conveys the problem and our approach, and then presents results from the THDA.

2. Experimental setup

The experimental setup used in the present study is shown in Fig. 1. It consists of a data acquisition and analysis system, a