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Diagnosis of PEM fuel cell stack dynamic behaviors

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Abstract

In this study, the steady-state performance and dynamic behavior of a commercial 10-cell Proton Exchange Membrane (PEM) fuel cell stack was experimentally investigated using a self-developed PEM fuel cell test stand. The start-up characteristics of the stack to different current loads and dynamic responses after current step-up to an elevated load were investigated. The stack voltage was observed to experience oscillation at air excess coefficient of 2 due to the flooding/recovery cycle of part of the cells. In order to correlate the stack voltage with the pressure drop across the cathode/anode, fast Fourier transform was performed. Dominant frequency of pressure drop signal was obtained to indicate the water behavior in cathode/anode, thereby predicting the stack voltage change. Such relationship between frequency of pressure drop and stack voltage was found and summarized. This provides an innovative approach to utilize frequency of pressure drop signal as a diagnostic tool for PEM fuel cell stack dynamic behaviors.

Keywords: PEM fuel cell; Pressure drop; Frequency; Dynamic behavior; Diagnostic tool

1. Introduction

The PEM fuel cell has been regarded as an ideal power source for a variety of applications due to its significant advantages, *i.e.*, high efficiency, low emission, silence and simplicity [1]. Presently, the PEM fuel cell is the top contender under research and development compared with other mainstream types of fuel cells. This is mainly because the PEM fuel cell has high power density and low operating temperature. Due to the complex physics behind PEM fuel cell electrochemistry, the dynamic behaviors of PEM fuel cell have not been fully studied and understood. Also, the transience of PEM fuel cell after start-up/load-change is more difficult to model than the steady-state performance. It has been gradually realized that studies on the dynamic behaviors is extremely important as the fuel cell stack will always experience transience during start-up, shutdown and switch of power requirement in portable and automotive applications. Identification of the physics behind the dynamic behaviors, the proposal of diagnostic tools and corresponding control method during transience will provide potential solutions for improving stack durability, efficiency and optimizing system development.

Many modeling studies on PEM fuel cells have been performed. In this paper, the authors focus on the dynamic modeling studies. One of the earliest dynamic models was developed by Amphlett et al. [2], which predicted the cell voltage, power and stack temperature as a function of time when the stack experienced perturbations. They considered the stack as a whole (without consideration of temperature gradient and local current variation) to develop the model as it was the earliest attempt in modeling study. Shan and Choe [3] developed an improved dynamic model for PEM fuel cell stack considering temperature effects. They conducted simulations to analyze start-up behaviors and the performance of the stack in conjunction with the cells. Yan et al. [4] extended their previous steady model of reactant transport to an unsteady one, which was employed to examine the transient transport characteristics and the system performance of PEM fuel cells. Their model was based on the assumption of two-dimensional mass transport in the cathode. Recently Shimpalee et al. [5,6] used a commercial computational fluid dynamics (CFD) solver to simulate the transient response of a PEM fuel cell subjected to a variable load and particularly focused on the overshoot/undershoot behavior under different flow stoi-

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chiometry conditions. Their modeling study was based on their previous experimental observation of overshoot/undershoot in transience [7,8]. Yu et al. [9] developed a water and thermal management model to study the steady-state and dynamic performance of a Ballard® PEM fuel cell stack, a commercially available product. Their results showed the stack taking about 30–40 min to reach the steady-state conditions, which was further verified by the real operation. Wu et al. [10] considered four main transient processes in a PEM fuel cell including species transport, electric double layer charge/discharge, membrane hydration/dehydration and heat transfer and proposed a rigorous transient model accounting for all four transient mechanisms. Their model, although adopting a two-dimensional modeling domain, is one of the most comprehensive and advanced currently available in the literature. Wang and Wang [11,12] developed a three dimensional dynamic model considering all the important transient processes in PEM fuel cells including gas transport, water accumulation in the membrane and double layer discharge. Their model is also one of the most advanced in open literature, which features the prediction of overshoot/undershoot during step changes under some operating conditions.

Experimental studies on PEM fuel cell dynamic behavior are few in open literature. Hamelin et al. [13] studied the transience of a PEM fuel cell under fast load communications and reported the faster fuel cell system response time than the load communications. Kim et al. [7,8] reported the influences of reservoirs, fuel dilution and gas stoichiometry on the dynamic behaviors during load changes and they observed the overshoot/undershoot of the current density during cell voltage switch. This is an important phenomenon that indicates the physics of the dynamic behaviors of PEM fuel cells, however it is still not well understood and controlled. Recently Yan et al. [14] conducted an investigation on the dynamic behaviors of PEM fuel cells under a series of changing parameters, *i.e.*, the feed gas humidity, temperature, feed gas stoichiometry, air pressure, fuel cell size and flow channel pattern. The authors reported that all of those parameters have significant influence on the transient response. Although they provided an overall experimental data for validation of related fuel cell models, they did not focus on any parameter to further identify the effects on the transience. Philipps et al. [15] explored the behaviors of a dynamically operated large-scale (11.5 kW) fuel cell system. Their research showed that a power-dependent modulation of the feed gas pressure and flow rate was necessary to achieve high energy efficiency.

It should be noted that although a number of experimental studies have been performed on dynamic behavior of PEM fuel cells and found in the literature, the research is still at initial stages. Most publications display the bulk experimental data during the transience under various operating conditions. Nonetheless, the significant physics that produces the unique transient response observed in the experiments, such as water flooding and removal, have not been thoroughly studied and understood. On the other hand, studies on the dynamic behaviors of a PEM fuel cell stack are limited in the literature compared with those involving a single cell. Dynamic behavior of a single cell and a stack is completely different, which can be theoretically explained by the more complicated mass transport, local current distribution and water management. Such difference has also been experimentally observed [14]. For example, it is evident that for dynamic behavior of a fuel cell stack, one or several cells may experience serious output decay while others remain in normal status, which is detrimental to the stack durability. Therefore, it is necessary and worthwhile to investigate the dynamic behaviors of a stack so as to provide experimental data for stack design and system control. Finally, the unstable voltage has been observed as a significant phenomenon in dynamic behavior. However, few studies have focused to correlate such voltage change in transience with pressure drop across cathode/anode, which is potentially a diagnostic tool for controlling stack output. Barbir et al. [16] and He et al. [17] conducted preliminary studies on pressure drop as a diagnostic tool for water flooding in PEM fuel cell. Nevertheless, they investigated steady cases only and did not explore the general relationship between pressure drop and cell voltage. Consequently, their methodology and conclusion may not be applicable to different cases although as a preliminary investigation their findings were of great significance. Numerically, Jiao et al. [18,19] reported the unsteady pressure drop across the stack using FLUENT® aided simulation, which was correlated with the liquid water transport behavior. Their study suggested that the pressure drop oscillation could be utilized as a diagnostic tool for water behavior. There is hardly any other publication in literature that concerns pressure drop as a diagnostic tool in fuel cell operation. A more thorough study on pressure drop as a diagnostic tool in dynamic stack operation is thus very necessary, which not only aids the understanding of physics in stack dynamic behaviors but also extends the previous research with regard to pressure drop.

2. Experimental

In the present study a 10-cell commercial PEM fuel cell stack from Palcan Power Systems Inc., was operated under a variety of conditions using the self-developed PEM fuel cell test stand. The authors would like to note that the overall performance of the commercial stack under test was not satisfactory with respect to the maximum attainable current density. Conversely, the purpose of the study was to explore the physics behind such phenomenon thus is not aimed to show the superiority of the design of this fuel cell stack.

2.1. Experimental setup

A PEM fuel cell test stand was self-developed as part of the project. It can monitor and/or control all operating parameters relating to PEM fuel cell performance including mass flow rate of the reactants, absolute pressure of the reactants, pressure drop across cathode/anode, stack temperature, gas temperature at inlet/outlet, humidity of the reactants before entering the stack, current drawn from stack and stack voltage and power. It features self-developed LabVIEW codes that is friendly interfaced with users, which can implement the instrument control, display and record data in a real-time format, and monitor the necessary parameters to prevent potential danger such as stack overheating. Not only the steady-state performance, but also the dynamic