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Experimental and computational study on the dynamic interaction between load variation and back pressure control in a polymer electrolyte membrane fuel cell for automotive application

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ARTICLE INFO

Article history:
Received 2 December 2014
Received in revised form
14 July 2015
Accepted 20 July 2015
Available online xxx

Keywords:
Polymer electrolyte membrane fuel cell
Dynamic modeling
Back pressure
Transient response
Operation strategy

ABSTRACT

Experimental and computational study on the operating characteristics of the fuel cell with changing back pressure at the cathode and anode outlets was performed for both steady and transient operations. In the experiments, the back pressure was controlled by a pressure regulator in the fuel cell outlet, and the effects of the operating pressure under various load conditions were observed in steady-state operations. The transient responses of the fuel cell to the load changes in different operating pressures were also examined. Additionally, in order to fully understand the effects of the major parameters in various operating pressures on the fuel cell performance, a dynamic simulation model of the cell stack was developed. The performance analysis revealed that a higher voltage was produced by the cell when a high pressure was maintained because the high pressure facilitated high concentration of the reactant gas near the membrane. The mass flow rate of the liquid water also increased with increasing pressure in a given humidity, which helped to maintain higher voltage than otherwise. However, the overshoot and undershoot of the output voltage during load transition also increased with increasing back pressure, primarily because of the difference between the rates of gas supply to the membrane and gas consumption near the membrane. Whereas the consumption of the gas near the membrane was rapid, the fresh reactant gas required some time to reach the membrane. The inherent time lag resulted in undershoot and overshoot with changing load. It was observed that the remaining liquid water was also an important factor which affected the level of undershoot or overshoot during the load change. Finally, an operating strategy using a back-pressure regulator was suggested and applied in a transient operation of irregular multi-step load variation. The back pressure should be decreased before the load change and restored back to the pre-set level for the steady-operation. The former was shown to reduce the size of undershoot or overshoot during transition, and the latter could lead to the efficient operation by reducing parasitic losses in the fuel cell system.

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http://dx.doi.org/10.1016/j.ijhydene.2015.07.101

Please cite this article in press as: Kim DK, et al., Experimental and computational study on the dynamic interaction between load variation and back pressure control in a polymer electrolyte membrane fuel cell for automotive application, International Journal of Hydrogen Energy (2015), http://dx.doi.org/10.1016/j.ijhydene.2015.07.101

Introduction

Over the last few decades, polymer electrolyte membrane (PEM) fuel cell has received much attention in diverse areas of research and development owing to its high energy efficiency, low emission, and low environmental impact. They are particularly attractive for use in automobiles considering their relatively compact size and low operating temperature. Thus, the market of the PEM fuel cells has been continuously growing, especially in the automotive sectors [1].

In the meantime, however, many of the previous studies on PEM fuel cell vehicle could not reflect an operating condition that may be experienced in real driving situations [2–6].

Most previous studies focused on the effects of operating parameters on the steady-state performance of the fuel cell stack, while the studies on dynamic behaviors were usually performed for the controller design by using simplified modeling [7–13]; few studies have attempted to explain the important phenomena regarding the results of the fuel cell in transient state. Especially, there is either undershoot or overshoot in the output voltage occurring with the load changes [14–18], but, previous studies have treated the phenomena only from the control perspective without an effort to reveal the reason of occurring the transient peaks. Since undershoot and overshoot on the output voltage during the load change may disturb stable operation of the fuel cell system, it is important to reduce the size of its peak. For example, if overshoot is occurred, overvoltage generated from the stack can damage the other parts of the system. In case of undershoot, the fuel cell can be shut down due to the low output voltage.

Mostly recently, several vehicle manufacturers implement variable-pressure fuel cell system to downsize the fuel cell stack while optimizing its performance throughout operating range. Operating pressure is typically changed by using the intake blower or compressor, while a back pressure regulator is considered as a promising passive device to further control the target pressure with its low power consumption and fast response time [19,20]. There were only few studies about the effect of back pressure regulation on the performance. For example, Zhang et al. performed computational study, but only considered the steady-state performance [19].

In this study, we analyze the influence of the back pressure regulation on the performance of the fuel cell and suggest a strategy of changing the pressure level during transient operation to minimize the undershoot and overshoot of the output voltage when using a back pressure regulator. We examined four different operating conditions, the combination of which could be similar to those encountered during real driving situation. These are steady state, operating pressure change, load step-up & step-down, and irregular multistep load conditions. In experiments, we installed an electronic back pressure regulator to change the back pressure at the cathode and anode outlets. We also developed a dynamic model, based on the previous works [21–27].

In the present paper, the discussion begins with the analysis of steady state results, in order to understand the proper operating pressures depending on the current density region. Next, the back pressure is varied under constant load condition to observe the transient behavior of the fuel cell operating pressure and its effect on the output voltage. Then, we perform load step-up and load step-down under different operating pressures, which demonstrate the effect of the pressures on the amount of overshoot or undershoot. Finally, these findings are used to develop an operation strategy which is applied under irregular multistep load variation.

Operating conditions

We prepare four different operating conditions which can happen in real driving situation: the one is a steady state condition, and the three others are transient conditions. In the steady state condition, the current density was alternately varied between 0.4 and 1.0 A/cm^2 under different back pressures. This enabled the observation of the effects of pressure on the output voltage in the steady state. Secondly, we varied the back pressure under constant load to observe the corresponding transient behavior of the fuel cell stack pressure and output voltage. The back pressure was increased in steps of 0.3 bar between 1.0 and 1.9 bar while the mass flow rate and all other parameters were maintained constant. Thirdly, we implemented load step-up and step-down to demonstrate the transient behavior of the output voltage, e.g. undershoot and overshoot. The former corresponds to the minimum value in the voltage curve when the current density is suddenly increased, and the latter to the maximum value during the sudden drop of current density. To demonstrate undershoot, the current density of the fuel cell was initially maintained at 0.5 A/cm^2, and then increased to 0.9 A/cm^2 and 1.3 A/cm^2, respectively. These three current densities were chosen to represent low, medium, and high load conditions in a typical PEM fuel cell operation. Conversely, overshoot was demonstrated by implementing load step-down, and the output voltages for current density changes from 1.3 to 0.5 A/cm^2 were analyzed. These test results led to the understanding of the interaction between the fuel cell loads and the back pressures. All the above operating conditions were analyzed both experimentally and numerically.

Lastly, we proposed an operating strategy using the back pressure regulator under irregular multistep load variation in experiment. To consider all the possible conditions in the real driving operation, such as low and high loads, sudden load drop and rise, and constant load, we randomly varied the current density. The current density was initially maintained at 0.3 A/cm^2, then sequentially stepped up to 0.8 and 1.3 A/cm^2, and subsequently stepped down to 1.0 and 0.4 A/cm^2. It was thereafter stepped up to 1.0 A/cm^2 again, and finally stepped down to 0.6 A/cm^2.

Methodology

In this section, we introduce the experimental apparatus and the modeling descriptions, which are followed by the model validation against the experimental results.

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