INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2015) 1–11

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/he

Modeling and simulation of parallel DC/DC converters for online AC impedance estimation of PEM fuel cell stack

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ARTICLE INFO

Article history:
Received 27 September 2015
Received in revised form
23 November 2015
Accepted 25 November 2015
Available online xxx

Keywords:
Polymer electrolyte membrane fuel cell
AC impedance estimation
Parallel DC/DC converters
Equivalent circuits

ABSTRACT

The electrochemical impedance spectroscopy (EIS) technique is now widely used in the study of the hydrogen polymer electrolyte membrane fuel cell (PEMFC), especially the diagnosis of flooding and drying. Though the working conditions of fuel cell vehicles is fairly rough with large electromagnetic interference and ever-changing environment, lots of efforts have been made to prompt the online EIS analysis of PEMFC stack in vehicles, such as using a DC/DC converter based on the ripple currents or active voltage control and so on. Considering the practical topologies of fuel cell powertrain systems, their researches inspire us to put forward a simpler approach in terms of applicability and controllability. For this reason, a topology of two parallel boost DC/DC converters for online AC impedance estimation of PEMFC stack is proposed. This topology is modeled using Matlab/Simulink. To better understand the electrical characteristic of PEMFC, equivalent circuits are utilized to model the PEMFC based on the electrochemical reactions and mass transport properties in the fuel cell. Fluctuation signals produced by a DC/DC converter are injected into the stack. The other DC/DC converter is used to adjust the output characteristic of the stack to the output voltage and current requirements of the external power devices and load. In this way, the fluctuation signal generation and power conversion are decoupled, which is more suitable for different applications of PEMFC stack. To effectively control these converters, closed-loop PI controllers are adopted and coefficients are regulated according to the frequency of disturbance signals. Based on this model, simulation results show that fluctuation signals are well generated and injected into the stack with low total harmonic distortion (THD). After analysis of the output voltage and current of the stack using FFT technique, AC impedance calculated is in consistent with the impedance characteristic of the equivalent circuits with high accuracy.

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http://dx.doi.org/10.1016/j.ijhydene.2015.11.129
0360-3199/

Introduction

Nowadays, the problems of energy crisis and environment pollution are becoming more and more serious. To reduce the demand for petroleum and lower greenhouse gases, the proton exchange membrane fuel cell, an electrochemical device that converts the chemical energy of oxygen and hydrogen to electricity, is attracting more and more attention from the whole world thanks to its high efficiency and low emissions [1–3]. During last two decades, much work has been done to improve the performance, costs and durability of PEMFC and a lot of achievements have been made with durability more than 10,000 h and costs less than half of before. However, two abnormal phenomena, namely flooding and drying [4], still have not been effectively controlled because sensors for water content detection are not fully developed and it is also very difficult to install them inside the stack.

When the fuel cell is applied to vehicles, complicated structures of fuel cell system and various working environment make it necessary to improve the understanding of the system dynamics. Many researches are concentrated on the physical modeling of fuel cell dynamics. Li et al. [5] reveals that the great distribution uncertainty of liquid water in the diffusion layer causes the difference of diffusion coefficients of each signal cell through theoretical analysis. They find that in the fast dynamic response process, oxygen concentrations between the surfaces of the catalysts differ greatly, resulting in the non-uniformity of transient voltage. Transient operating parameters significantly influence the performance by affecting the water transport dynamics and water content. Zina et al. [6] develops a two dimensional PEM fuel cell model which considers transient of mass, heat and momentum transfer in the gas channels and diffusers at both te anode and cathode sides. Their study visualizes the effect of permeability on the dynamic behavior of the velocity and pressure profiles in the flow field. Latha et al. [7] proposes a minimal order model to study the transient response of the fuel cell, and the model is tuned using steady state polarization curve and transient response of the cells during operation. Even if the operating conditions of the fuel cells remain constant, the internal states of them change with time. Kim et al. [8] studies the dynamic interactions between the back pressure and the loads through experiment and computation analysis. The back pressure influences the internal pressure of the air inside the flow channel and gas diffusion layer so it needs to be well controlled. Verma et al. [9] uses the two-dimensional finite element analysis to predict the mechanical response of the membrane under cyclic changes in operating load and in the humidity levels.

The complex physical and electrochemical processes inside the fuel cell make it rather difficult to fully understand internal states under the steady and transient operations. To observe these states, more and more intricate equations are needed to solve for online application, especially some partial differential equations. In consequence, the required computation efforts, especially when complex phase transformation of water happens, are relatively large and applying these analytical models to the vehicle controllers for online analysis of substance components distribution and water content identification cannot be realized easily.

Compared with physical modeling methods, the electrochemical impedance spectroscopy (EIS) has advantages of less computation, less measurement time and more feasible. Till to now, EIS has been widely used in the studies of PEM fuel cell [10,11]. The EIS describes the impedance characteristics of the fuel cell and the impedances in different frequency ranges represent different processes inside the fuel cell structure, including membrane water content and mass transport [12,13]. For example, a General Motors' patent presents the correlation between the membrane water content and the high frequency impedance [14].

Except in the stable states, the EIS method can also be used to capture the dynamics of the fuel cell, such as processes of the membrane hydration and gases transport. Wang et al. [15] investigates the time constants of both processes using mathematical analysis and experiment validation. The time constant of the membrane hydration is about 10 s and the time constant of gases transport 0.1 s–1 s. Hence, the frequency which is inversely proportional to the time constant of both processes is within the measurement frequency range of the EIS method. Furthermore, Wang et al. [16,17] studies the membrane hydration and water transport under load changes and they combine the experiment, the mathematical modeling and the EIS method together. Relations can be found between the realistic physics and the measured impedance of the cathode, the anode and the membrane. The EIS method is to study the electrochemical characteristics of the fuel cell and to better estimate the water content inside the fuel cell, the EIS method shall be combined with the mathematical method.

Usually, the preferable frequency range of the impedance spectroscopy is from 0.1 Hz to 1 kHz [18]. The reason is determined by two factors. At first, when the frequency of the fluctuation signal is below 0.1 Hz, the stability of the fuel cell system cannot be guaranteed. Secondly, when the frequency of the fluctuation signal is above 1 kHz, the inductive behavior from the wires is predominant. When measuring impedances of the fuel cell using EIS, a fluctuation signal, no matter whether it is of voltage or current, must be superimposed on the direct current output of the fuel cell. Fluctuation signals of this frequency range can be generated using circuits formed by semiconductors and power devices.

Roberto et al. [19] develops an instrument for EIS analysis of fuel cells composed of a function generator, a computer, a frequency analyzer and an electronic load. The load current drawn from the fuel cell is less than 10 A. In comparison with current of the fuel cell stack in vehicles as much as several hundred, this equipment maybe is more propitious to investigation of a single fuel cell of small sizes. Giovanni et al. [20] discusses the possibility to use the current ripple introduced by switching mode power converters for low-cost monitoring of PEMFC. Fuel cells and an electronic load are directly connected and the emulated three-phase and single-phase inverter ripples by means of the electronic load are injected into the fuel cell. Good experiment results are attained for diagnosis of PEMFC state-of-health. However, connecting the fuel cell stack with a DC/DC converter is gradually accepted by researchers and the ripple frequency of a DC/DC converter is just the same as the switching frequency of the power switching semiconductors such as IGBT. This method