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Original Research Article

Dynamic characteristics of an automotive fuel cell system for transitory load changes

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ABSTRACT

A dynamic model of Polymer Electrolyte Membrane Fuel Cell (PEMFC) system is developed to investigate the behavior and transient response of a fuel cell system for automotive applications. Fuel cell dynamics are subjected to reactant flows, heat management and water transportation inside the fuel cell. Therefore, a control-oriented model has been devised in Aspen Plus Dynamics, which accommodates electrochemical, thermal, feed flow and water crossover models in addition to two-phase calculations at fuel cell electrodes. The model parameters have been adjusted specifically for a 21.2 kW Ballard stack. Controls for temperatures, pressures, reactant stoichiometry and flows are implemented to simulate the system behavior for different loads and operating conditions. Simulation results for transitory load variations are discussed. Cell voltage and system efficiency are influenced by current density and operating temperature as well. Together, air blower and radiator consume 10% of the stack power at steady-state; nevertheless their power consumption could reach 15% during load surges. Furthermore, water crossover in the fuel cell has shown a significant impact on anode inlet flows, humidity and recirculation pump during these load changes. Also, the amount of water saturation at cathode is found to be abruptly fluctuating and its removal from cathode is dependent on operating temperature and reactant stoichiometry.

Introduction

Fuel cell systems have received substantial attention in recent years and research on these systems has drastically increased mainly due to their inherent virtues of clean and efficient mode of operation. Existing fuel cell systems are categorized based on the type of electrolyte and preferred operating conditions. Among various types of fuel cells, Proton Exchange Membrane Fuel Cells (PEMFCs) are currently the best choice for portable power generation due to their relatively low operating temperature, quick start-up, high power density and efficiency to name a few.

As a power source for automotive applications, PEMFC systems are usually subjected to inflexible operating requirements when compared to stationary applications. These systems have to operate at varying conditions related to temperatures, pressures, power load and humidity. PEMFC dynamics are influenced by reactant flows, heat management and water content in the streams as well as within the fuel cell itself. All the auxiliary components, such as air and fuel supply system which include compressors and control valves, and the thermal control system which consists of heat exchangers, coolant pumps and air radiators need to be controlled for the optimum operation of fuel cells when the system experiences varying load changes. Understanding the transient behavior of a PEMFC therefore becomes very beneficial in the dynamic modeling of these power modules at a system-level.

Many PEM fuel cell models have been developed in recent years. However, very few of these models are published on the dynamic modeling of complete PEMFC systems along with their BoP. Most of the available literature focuses on individual components of these systems, mainly on the fuel cell stack. While, steady-state models of these systems are present in abundance, a generalized dynamic model for the fuel cell stack is reported by Amphlett et al. [1]. Another bulk dynamic model used for developing a control system is presented by Yerramalla et al. [2]. A simplistic dynamic model based on cathode kinetics was developed by Ceraolo et al. [3]. Pukrushpan et al. [4] presented a transient dynamic model and elucidated the dynamic characteristics of water transport in PEM fuel cells. A complete PEMFC system model was developed by Pathapati et al. [5] which included the dynamics of flow and pressure in the channels. Hu et al. [6] represented a three-dimensional computational PEM fuel cell model with a comparison of different flow fields. In recent years, several improved models were published by Park and Choe [7] and Jia et al. [8] to investigate fuel cell transient electrical responses under various operating conditions.

Heat management in PEMFCs being a critical factor in its operations and performance is accounted for in the open literature as

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Nomenclature

E	theoretical voltage (V)	i	current density (A/cm^2)
V_{cell}	average cell voltage (V)	i_n	internal current density (A/cm^2)
$\dot{P}_{el}$	stack power (kW)	i_0	exchange current density (A/cm^2)
$\dot{P}_{in}$	energy into the fuel cell (kW)	$i_{0,a}$	anode exchange current density (A/cm^2)
$\dot{P}_{out}$	energy out of the fuel cell (kW)	$i_{0,c}$	cathode exchange current density (A/cm^2)
$\dot{Q}_{loss}$	heat dissipated (kW)	k_a	anode reaction rate (mol/scm^2)
C_t	stack thermal capacitance (kW)	k_c	cathode reaction rate (mol/scm^2)
R	universal gas constant (J/K)	n_e	electrons transferred (mol$_e$/mol$_{fuel}$)
T	temperature (K)	n_{el}	number of electrons (−)
F	faraday's constant (C/K)	n_{drag}	electro osmotic drag (−)
I	current (A)	t_m	membrane thickness (cm)
N_{cell}	number of cells (−)	α_a	anode transfer coefficient (−)
Δg_f^{-0}	change in Gibbs free energy (J/K)	α_c	cathode transfer coefficient (−)
P_{H_2}	hydrogen partial pressure (−)	β	symmetry factor (−)
P_{O_2}	oxygen partial pressure (−)	η_{act}	activation overpotential (V)
M_m	mol. weight of membrane (kg/mol)	$\eta_{act,a}$	anode activation overpotential (V)
J_{H_2O}	net water-diffusion flux (mol/scm^2)	$\eta_{act,c}$	cathode activation overpotential (V)
D_λ	water diffusion coefficient (cm^2/s)	η_{conc}	concentration overpotential (V)
a_{H_2}	hydrogen activity (−)	η_{ohmic}	ohmic overpotential (V)
a_{H_2O}	water activity (−)	λ	membrane water content (−)
a_{O_2}	oxygen activity (−)	ρ_{dry}	membrane density (g/cm^3)

well. Issues related to temperature dynamics are dealt with and studied by Vasu and Tangirala [9], which could predict the effects of temperature and feed flows on system transient behavior. Khan and Iqbal [10] proposed a transient model to predict efficiency in terms of voltage output, and a thermal model including heat transfer coefficients and energy balance for the stack. Shan and Choe [11] analyzed the temperature distribution on fuel cells by developing a two-dimensional model. Another control-oriented thermodynamic model is also proposed by del Real et al. [12]. Coolant control strategies were suggested by Ahn and Choe [13] after an investigation into temperature effects on the system. Jung and Ahmed [14] developed a stack model based on real-time simulator in the MATLAB/Simulink environment and validated it with the experimental setup of Ballard Nexa fuel cell. A thermal management system for a PEMFC was designed by Asghari et al. [15]. The influence of temperature on fuel cell's characteristics is also reported by Beicha [16].

The model presented in this study aims at an analysis and investigation of a complete PEMFC system and studies its transient response to varying load and operating conditions. According to the authors' literature survey, no studies have been conducted on the system-level dynamic modeling of PEMFC system with all the necessary BoP components. Previous studies focus on the transient response of the fuel cell stack under different operating conditions; primarily on individual component analysis. Therefore, a need for a control-oriented dynamic system model is identified, which simulates a fuel cell stack under multiple varying operating conditions and changing auxiliary component outputs. Dynamic characteristics of PEMFC are also attributed to heat management and water transportation that are scarcely reported in the open literature. Investigations into effects of heat exchangers on fuel cell stack performance and water crossover on anode recirculation operations are therefore selected to be one of the primary objectives here.

Therefore in the entirety of this study, a sizeable focus has been set to devise a dynamic model of the fuel cell stack, which accommodates electrochemical, thermal, feed flow and water transportation models. A complete system is constructed in Aspen Plus Dynamics by incorporating all the essential auxiliary components and implementing control strategies in order to emulate a real PEMFC system. Effects of these controls and other components are also investigated in this work. A thermal management strategy has been designed and its dynamic impact on the fuel cell stack has been reported for the first time. Analysis of water crossover in the fuel cell and its impact on anode recirculation operations has been conducted and suitable findings are reported here. Moreover, two-phase characteristics of concerning material streams are determined which provide suitable insight into saturated water issues in the fuel cell stack. This study also takes into consideration the BoP, such as air blower, valves, coolant pumps and air radiator; making it a thorough tool for predicting PEMFC dynamics and to provide important information for the design of control strategies.

In the current study, the focus is on a complete system with all necessary auxiliary components and their effect on system performance rather than effect of individual components on the system. Thus, it differs substantially from previous studies in the sense that not only dynamics of the fuel cell stack are included but responses of all other auxiliary components are also incorporated by applying a detailed control strategy design.

System overview

Layout of the proposed PEMFC system is shown in Fig. 1. The system comprises a PEMFC stack, air compressor, humidifier, pumps, heat exchangers and radiator for the cooling circuit, flow valves and controllers. Compressed air, which is fed into the cathode of the stack is cooled and humidified prior to its entrance. Pressurized hydrogen from storage tank is regulated by a control valve into the fuel cell anode. Since the stack is not operated at dead-end mode, a higher fuel stoichiometry is maintained. Unutilized fuel from the anode exhaust is recirculated back to the feed stream via a recirculation pump, thus allowing the fuel to be humidified.

In order to have a steady-state operation, the fuel cell stack needs to be maintained at a constant operating temperature. Therefore, the heat rejected by the stack is absorbed by a liquid coolant which circulates in a circuit associated with the stack and a heat exchanger. An external cooling loop, connected to the aforementioned heat exchanger, in turn cools the water in the internal circuit. This circuit also consists of a heat exchanger to precool the air entering the fuel cell and an air radiator for heat