Available online at www.sciencedirect.com

ScienceDirect

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

Air supply regulation for PEMFC systems based on uncertainty and disturbance estimation☆

Zhiyang Liu, Jian Chen, Hao Chen, Chizhou Yan*

State Key Laboratory of Industrial Control Technology, College of Control Science and Engineering, Zhejiang University, 38 Zheda Road, Hangzhou, Zhejiang Province, PR China

ARTICLE INFO

Article history:
Received 15 August 2017
Accepted 29 January 2018

Keywords:
Fuel cells
Air supply systems
Nonlinear control
Uncertainty and disturbance estimation

ABSTRACT

In this paper, a novel system analysis and controller design method for the air supply of proton exchange membrane (PEM) fuel cell systems is proposed. Firstly, a class of nonlinear systems with specific structures are introduced. In further analysis, the introduced system can be divided into two parts: one is fast and include disturbances and uncertainty, and the other is relatively slow. We change the introduced system into an equivalent cascade system. Some state variables of the first subsystem are acted as the inputs of the second subsystem. Furthermore, the similarities between the air supply system and the equivalent cascade system are proved, and a cascade controller is proposed based on uncertainty and disturbance estimation (UDE) and Lyapunov method. Moreover, we implement the algorithm in the air supply system for PEM fuel cells. Experimental results show the effectiveness of the proposed method.

Introduction

Nowadays environmental issues, such as global climate change and air pollution, have strongly attracted world's attention. Traditional fossil fuels are still the predominant energy source for human activity, which are responsible for many well-known environmental problems, typically the global warming due to massive CO_2 emissions and the air pollution due to the emissions of SO_x and NO_x [1]. Proton exchange membrane(PEM) fuel cells are gaining increased attention as viable energy generators for a range of applications [2]. However, the overall commercialization of fuel cell systems has not yet come due to the limited life time and high selling price [3]. To promote the development of this domain, many researches have been done to improve the durability and cut the cost. Among them, one of the most important research directions is system design and control. The results in [4,5], and [6] have shown that advanced control can improve the performance and reliability of fuel cell systems.

In general, A fuel cell system include four main subsystems: the fuel delivery subsystem that feeds the anode with fuel, the air supply subsystem that feeds the cathode with oxidant, the water and thermal management subsystem that maintain the humidity degree, and the temperature of fuel cell. Compared with the reactants supply, the control of humidity and temperature are much slower. Therefore, they can decoupled from the whole system under the consideration of controller design. For fuel delivery subsystem, the hydrogen is always stored in a high pressure tank and fed through a pressure reducing regulator. Because the purity of supplied hydrogen is always higher than 99.99%, the anode is always working on the dead end mode with a blower in the recirculation loop. To drain away the produced water and the

☆ This work is supported by the National Natural Science Foundation of China (61433013 and 61621002).

* *Corresponding author.*
E-mail address: jchen@zju.edu.cn (J. Chen).
URL: http://mypage.zju.edu.cn/jchen

https://doi.org/10.1016/j.ijhydene.2018.01.189

nitrogen cross cathode, the anode should be purged periodically. The control of fuel delivery subsystem is always focusing on the purge frequency and the flow rate in the recirculation loop. Compared with the fuel delivery subsystem, the air supply subsystem is driven by an air compressor which is a relatively slower mechanical device [5]. Due to the dynamics of the compressor and the air supply manifolds, there could be a large time delay during the air supply. When the load current changes abruptly, it may lead to oxygen starvation in the cathode. Oxygen starvation may further result in cell output voltage degradation, stack flooding, and even reducing fuel cell's lifetime [7]. Furthermore, a sires of experiments have been done in [8] and the results show that at the baseline oxygen excess ratio of 1.50, the generated water under the load change blocked the gas channel and gas diffusion layer (GDL), resulting in the increase in the mass transport resistance. Therefore, our work is concentrated on oxygen excess ratio control of air supply system.

To describe the air supply system, many researches have been done. Some of the researchers used the equivalent circuit method to model the system [9]. Although, this method can describe the dynamics of the system with very small errors, if the structure of the system changed, it is complex to fix the model. Others are focusing on the mechanisms of the system. Based on physical principles of the fuel cell air supply system, a ninth order nonlinear model is proposed in [7]. In [10], the model in [7] is reduced to 4th order with reasonable assumptions. The authors in [5] proposed a reduced 3rd order model by replacing the partial pressures of oxygen and nitrogen in [7] with the cathode pressure. Based on the work in [5], the researchers improve the accuracy of 3rd order model by identifying the dynamics of air compressor with many polynomials in [11]. However, these polynomials can not cover the whole working rang of compressor. At the uncovered operating point, they use the closest polynomial to estimate the characteristics.

As for controller design, at the very beginning, many researches are based on linear controller with simulation results. The works in [7] is one of the most classical researches about modeling and control of the fuel cell systems. In that research, the authors make linearization of the air supply system based on a 9th order model, and give some elementary simulation results about the control of oxygen excess ratio. Although, the controller is difficult to realize in a real system, it still inspires the following researches. In [12] and [13], a feedforward controller is designed based on partial identified models and give some simulation results. A passivity and robust PI control of the air supply system is developed based on a local linearized model in [14]. The authors also show good simulation performance, but the stability can be only guaranteed at the equilibrium point. In [4], a high order observer-based sliding mode controller is designed and a novel procedure to tune the controller parameters which allows the designer to affect the steady-state behavior of the output response in a quite direct and transparent manner. Simulation results also show the effectiveness of this method. A novel hybrid fuzzy-PID control scheme is proposed in [15], they are focused on implementing the controller in a sensorless control scheme and give some primary simulation results on it. Furthermore, there are also many literatures focus on realizing the controller is the physical or semi-physical systems. A sub-optimal second order sliding mode controller in a semi-physical system is proposed in [16]. In this system, the air supply system is built by physical components and the fuel cell stack is replaced by a real-time emulation system. Although the emulation system has some model errors with the physical system, it is still a good method to verify the control algorithm because of the simplicity. For realizing the control algorithm in a real system [17–23], have tried many different nonlinear control algorithm for the air supply system in the real fuel cell systems with good performance.

In this paper, a novel system analysis and controller design method for the air supply of PEM fuel cell systems is proposed. Firstly, a class of systems with a specific amount of properties are introduced. Based on the physical properties, the introduced system can be transformed into an equivalent cascade system. In the new cascade system, some state variables of the first system are the inputs of the second system. Based on model analysis, we prove the similarities between the introduced system and the air supply system for PEM fuel cell. A cascade controller based on disturbance and uncertainty estimation (UDE) and Lyapunov theories are designed for this system. We also give the details for the implementations of the controller in a real time control system. Through the experimental results, we prove the proposed controller is easy to regulate the parameters and also with good performance.

System description

In general, we can describe most of physical systems as the following form:

$$\dot{x}(t) = f(x,t) + \Delta f + (g + \Delta g)u(t) \tag{1}$$

where $x(t)\in\mathbb{R}^n$, and $u(t)\in\mathbb{R}^k$. Among these systems, there is a class of systems whose control input can only directly affect the first b state variables and the output is only depend on the rest of d state variables x_d. Moreover, the two parts are based on different mechanisms which lead to that the uncertainty of the model are also only exist in the first b state equations. This class of systems can be described as the following equations:

$$\begin{aligned} \dot{x}_b(t) &= (A+\Delta A)x_b(t) + (B+\Delta B)u(t) + f_1(x_b(t), x_d(t)) \\ \dot{x}_d(t) &= f_2(x_b(t), x_d(t), t) \\ y(t) &= h(x_d(t)) \end{aligned} \tag{2}$$

where $x_b(t)\triangleq[x_1(t)\cdots x_b(t)]^T$ is the set of the fist b state variables of $x(t)$, $x_d(t)\triangleq[x_{b+1}(t)\cdots x_n(t)]^T$ is the set of the rest d sate variables of $x(t)$, $u(t) = [u_1(t)\cdots u_k(t)]$ is the control input of the system, the full rank matrix $A\in\mathbb{R}^{b\times b}$ and $B\in\mathbb{R}^{b\times k}$ are the known parameters of the model, ΔA and ΔB are the model uncertainties, $f_1(x_b(t), x_d(t))$ is the nonlinear part of the state equation.

In further analysis, the system can be separated into two subsystems as follows:

$$\begin{cases} \dot{x}_b(t) = (A+\Delta A)x_b(t) + (B+\Delta B)u(t) + f_1(x_b(t), \xi(t), t) \\ y_1(t) = x_b(t) \end{cases} \tag{3}$$

$$\begin{cases} \dot{x}_d(t) = f_2(x_d(t), \tilde{u}(t), t) \\ y_2(t) = h(x_d(t)) \end{cases} \tag{4}$$

with $\xi(t)\triangleq x_d(t)$ and $\tilde{u}(t)\triangleq x_b(t)$. It is obviously that the state variables $x_d(t)$ are regarded as unmeasurable disturbance in