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Robust control of the PEM fuel cell air-feed system via sub-optimal second order sliding mode

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HIGHLIGHTS

- Control of air-feed system of Polymer Electrolyte Membrane Fuel Cell (PEMFC).
- Nonlinear modeling of fuel cell with formalization of parametric uncertainties.
- Robust nonlinear second order sliding mode controller in cascaded structure.
- Hardware-In-Loop simulation based on a commercial twin screw air compressor and a real time fuel cell emulation system.

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ABSTRACT

This paper is focused on the control of air-feed system of Polymer Electrolyte Membrane Fuel Cell (PEMFC). This system regulates the air entering in the cathode side of the fuel cell. The control objective is to maintain optimum net power output by regulating the oxygen excess ratio in its operating range, through the air compressor. This requires controllers with a fast response time in order to avoid oxygen starvation during load changes. The problem is addressed using a robust nonlinear second order sliding mode controller in cascaded structure. The controller is based on sub-optimal algorithm, which is known for its robustness under disturbances and uncertainties. The controller performance is validated through Hardware-In-Loop (HIL) simulation based on a commercial twin screw air compressor and a real time fuel cell emulation system. The simulation results show that the controller is robust and has a good transient performance under load variations and parametric uncertainties.

1. Introduction

1.1. Antecedent

Fuel cell is an electrochemical system which produces electricity through redox reaction between hydrogen and oxygen [1]. Fuel Cells are under extensive development for many power applications due to high efficiency, abundance of fuel (hydrogen and oxygen) in nature and lower pollutant emission as compared to fossil fuels. They have been studied as stand-alone power sources [2] as well as hybrid power sources [3,4]. Polymer Electrolyte Membrane Fuel Cells (PEMFCs) are particularly suitable for usage in transportation (passenger cars, buses, aircrafts) due to their fast startup time, high power density and favorable power-to-weight ratio [5,6].

A major problem in PEM fuel cell operation is oxygen starvation during rapid load changes. This occurs during sudden increase in load which accelerates the chemical reactions inside the fuel cell, resulting in increased oxygen consumption. This results in a sudden decrease in the oxygen pressure and the stack voltage, causing a hot spot or burn through on the surface of a membrane [7]. To avoid oxygen starvation, the oxygen excess ratio in the cathode needs to be maintained greater than 1, which requires precise control of the air-feed system. Presence of excess oxygen protects the fuel cell from starvation and the related physical damage.

The air-feed system of a PEMFC consists of a motorized air compressor connected to the cathode via a supply manifold. Its performance has a great influence upon the overall dynamic performance and transient response of the fuel cell under load change [8]. As fuel cells cannot tolerate contamination and pulsations in pressure and air-flow, the compressor needs to be chosen carefully and used with a precise controller. High-end compressors, equipped with filters and leak-proof lubrication systems are inevitable in spite of their cost and power inefficiency. The compressor motor is

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powered by the fuel cell itself and can consume up to 20% of the fuel cell power [7,9]. The net power output of a fuel cell is actually the total power produced minus the power consumed by the compressor. Maintaining an optimal excess ratio also permits to optimize the net power output of the fuel cell [7]. Therefore good compressor control is essential to the performance of the entire fuel cell system.

1.2. Literature review

In the last few years, many control strategies have been proposed for control of the PEMFC air compressor, aimed at maximizing the net power output and avoiding oxygen starvation. It is known that the highest net power can be achieved at an oxygen excess ratio (λ_{O_2}) between 2 and 2.5 as seen in Fig. 1 [7]. However, in contemporary literature, a constant value $\lambda_{O_2} = 2$ is used, under consideration that it presents minor deviations all over the system operation range. Initial work, done in [7], considered the entire PEMFC control as one complete problem, which included the air-feed system control. Feedforward and LQ techniques were employed after linearizing a ninth-order nonlinear model of the PEMFC at an operating point. In [10], the dynamics of the air-feed system were decoupled from the rest of the PEMFC, and a reduced 4-state model was introduced. A proportional integral controller was designed using this model. Model Predictive Control (MPC) of oxygen excess ratio has also been studied extensively in the literature and many important results have been published, such as [11–14]. Notably, in [13], an MPC was developed using the compressor motor voltage to manipulate the air flow rate entering the fuel cell, and in [14], a nonlinear model predictive control (NMPC) strategy was proposed using Volterra series. Among other control techniques, an LQR/LQG strategy for oxygen stoichiometry control is presented in [15], where the control design is based on a linearized model of the plant (Fuel Cell). In [16] a real time implementation of sliding mode control is applied to avoid the oxygen starvation in a PEMFC. In [9,17], the authors have further reduced the four-state model of Suh [10], into 3 states by replacing the partial pressures of oxygen and nitrogen by the cathode pressure, under the assumptions that molar mass of oxygen, nitrogen and water have almost the same magnitude and the air-flow in the cathode is choked. Then a higher order sliding mode controller has been designed using super-twisting algorithm. Despite that the simplified model used in [9,17] has a structure which is more suitable for controller design, it has not been formally validated in all range of the operating region. A different process of optimizing the delivered power of fuel cell has been presented in [18,19], using an extremum seeking controllers. Extremum seeking is an effective method for optimization problems when the system dynamics are not well known. However, as this method requires the optimal operating point to be found through excitation of system dynamics, it is slow and not preferred when the system model is known.

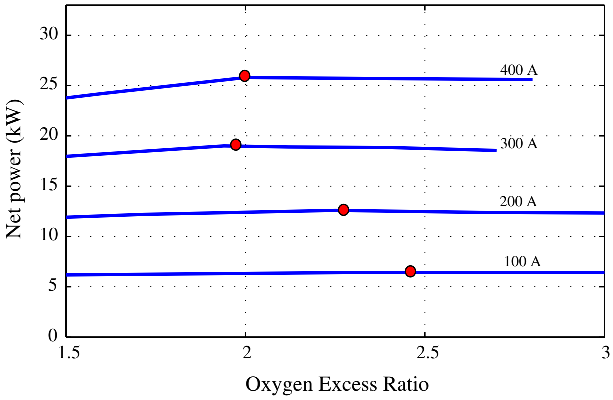

Fig. 1. Net power as a function of oxygen excess ratio at different stack current.

In the above cited works, the parameters of the fuel cell air subsystem have been considered as constants. This is not true in practice, as these parameters vary over time because of events such as clogging of air filters and contamination of gas diffusion layers as mentioned in [20]. Variations in operating conditions, such as temperature, humidity, reactant volumes and compressor parameters, also influence the system parameters. Therefore it is necessary to consider parametric uncertainty during control design, to develop robust controllers. For example in [21], parametric uncertainties have been incorporated in several parameters of the system. Then, under the hypothesis that supply manifold pressure dynamics can be neglected, a static relation between the optimal oxygen excess ratio and the compressor flow rate reference has been established. Then, super twisting sliding mode controller has been designed to force the compressor to maintain this flow rate reference. In [22], parametric uncertainties have been integrated in the model, then a robust controller based on super twisting algorithm is applied.

1.3. Motivation

In this paper, we are not just interested in regulating the oxygen excess ratio, but also in ensuring that it is maintained at its optimal value so that the net power output is optimized. The optimal oxygen excess ratio is calculated as a function of stack current. To achieve this objective, a sub-optimal algorithm based robust second order sliding mode controller (SOSMC) is used for air compressor control. It can be noted that sliding mode control has already been applied for fuel cell related applications, such as stack breathing control in [21] and power management in [23]. The proposed control law is based on the works of [24–29], which have been developed to counteract the chattering phenomenon and to maintain robustness and finite time convergence properties of classical sliding mode under load variations and parametric uncertainties.

1.4. Contribution

The proposed controller has a cascade structure which consists of two blocks: (1) a SOSMC-based oxygen excess ratio control loop that provides a reference command velocity; and (2) a SOSMC-based velocity control loop generating the motor quadratic current (as shown in Fig. 2). The nonlinear dynamic model of the air-feed system, used for control design, is based on the 4 state model proposed by Suh [10]. The advantage of this model, as compared to the reduced model used in [9,21], is that it is valid in the complete operating range of a fuel cell and the pressure dynamics are not neglected. In addition, parametric uncertainty is formally described and included in the model. By this method, uncertainty is taken into account directly during controller design. The resultant nonlinear controller is robust and is proven to guarantee performance around any equilibrium point and under parametric uncertainty.

Experimental validation of the presented controller is carried out on an instrumented HIL test bench that consists of a real commercial compressor and a real time fuel cell emulation system [30,31]. The data acquisition and control prototyping system installed on the test bench has fast data transfer capabilities and it is equipped with a real time controller for implementation of control algorithms. The experimental results obtained from the test bench show that the closed loop system is stable and has good transient characteristics.

This paper is divided as follows: The dynamics of the PEMFC air-feed system have been modeled in Section 2. In Section 3 the