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Fault tolerance control for proton exchange membrane fuel cell systems

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HIGHLIGHTS

- A scheme that simultaneously performs fault diagnosis and tolerant control is proposed.
- A model-based fault detection method is used to detect flooding and membrane drying.
- Three controllers based on feedback linearization methods are built.
- Voltage and pressure difference can be controlled stable in fault-free and faulty states.

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ABSTRACT

Fault diagnosis and controller design are two important aspects to improve proton exchange membrane fuel cell (PEMFC) system durability. However, the two tasks are often separately performed. For example, many pressure and voltage controllers have been successfully built. However, these controllers are designed based on the normal operation of PEMFC. When PEMFC faces problems such as flooding or membrane drying, a controller with a specific design must be used. This paper proposes a unique scheme that simultaneously performs fault diagnosis and tolerance control for the PEMFC system. The proposed control strategy consists of a fault diagnosis, a reconfiguration mechanism and adjustable controllers. Using a back-propagation neural network, a model-based fault detection method is employed to detect the PEMFC current fault type (flooding, membrane drying or normal). According to the diagnosis results, the reconfiguration mechanism determines which backup controllers to be selected. Three nonlinear controllers based on feedback linearization approaches are respectively built to adjust the voltage and pressure difference in the case of normal, membrane drying and flooding conditions. The simulation results illustrate that the proposed fault tolerance control strategy can track the voltage and keep the pressure difference at desired levels in faulty conditions.

1. Introduction

Proton Exchange Membrane Fuel Cell (PEMFC) is a good alternative source for the transportation area compared to the conventional combustion vehicle, due to its lower pollutant emissions and higher efficiency. For PEMFC systems, enabling the plant to follow the load is an important control goal. Because load transients often involve significant peaks in power relative to the steady-state load, which may have a significant impact on the life of PEMFC systems [1]. Moreover, too high pressure difference between the anode and cathode may damage the PEMFC membrane [2]. Thus maintaining a proper pressure difference is another primary control task for PEMFC systems.

In the last ten years, plenty of works have been carried out on the load and pressure control for the PEMFC systems. Wang et al. [3–8] designed several robust controllers to provide steady load for various PEMFC systems, including a robust PID controller, an H infinity controller and a reduced-order controller. The convex linear matrix inequality algorithm was proposed to the construction of the state-feedback control law to adjust the PEMFC output voltage in Refs. [9–11]. Ref. [12] utilized an exact linearization method to keep the voltage stable under the disturbance caused by load changes. An adaptive fuzzy logic controller was built to control the PEMFC voltage stable in Ref. [13]. A PI controller was employed to regulate the PEMFC power in Ref. [1]. Ref. [14] proposed a nonlinear voltage-mode controller to maintain the PEMFC voltage stable. In

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Ref. [15], a second order sliding mode controller was proposed to keep the PEMFC anode and cathode gas pressures equal. In Refs. [16,17], based on feedback linearization methods, two controllers were developed for keeping the hydrogen and oxygen pressures at the desired values. In Ref. [2], a sliding mode controller was built to keep the pressures of hydrogen and oxygen at the desired values despite of load changes. The above studies can effectively track the PEMFC load and keep the pressure steady near the enactment value in working. However, these literature does not take into account the impact of faulty conditions on the PEMFC instantaneous performance, which are limited to control design under PEMFC nominal operating conditions. Besides, no literature discusses how to simultaneously control the voltage and pressure for the PEMFC.

Flooding and membrane drying often occur during PEMFC operation, which may lead to performance losses, irreversible degradations and even systems failure [18]. Thus, in order to increase the PEMFC system stability and durability, different diagnosis methodologies for flooding and membrane drying have been presented. These works can be sorted in two main categories: 1) model-based fault diagnosis methods. Firstly build a PEMFC model, which includes black models [18–21] or physical models [22]. Then compute the instantaneous remoteness between the real PEMFC behavior and the expected healthy behavior. Last through the residue analysis, faults can be detected. A complete study on PEMFC model-based diagnosis methods was done in an overview [23]. 2) non-model-based fault diagnosis approaches. These methods involve electrochemical impedance spectroscopy (EIS) methods [24–26] and empirical mode decomposition (EMD) algorithm [27]. A thorough review of non-model-based diagnosis approaches for PEMFC systems has been conducted in Ref. [28].

Even if PEMFC fault diagnosis and control approaches have been widely proposed, links between fault diagnosis and control techniques are still lacking. In Ref. [29], based on a model predictive control(MPC) method, a tolerance control strategy was proposed to keep the oxygen excess stable under the circumstances of compressor voltage and air valve opening area faults. In Ref. [30], using Quasi-linear parameter varying (qLPV) methods, the oxygen excess was controlled stable under various types of faults. The above two works didn't implement fault diagnosis for the PEMFC system, which supposed the fault diagnosis tool available. In Refs. [31,32], using PID controllers, two complete fault tolerance strategies were proposed to control the oxygen excess, while they simultaneously performed fault diagnosis and fault tolerant control for the PEMFC systems. However, these fault tolerance control strategies only discuss the oxygen excess control under fault conditions.

Motivated by the above need, in this work a unique fault tolerant control for the PEMFC system is developed, which can track the PEMFC voltage and keep the pressure difference steady in the case of normal and fault conditions (membrane drying and flooding). The proposed tolerance control scheme for the PEMFC includes three parts: a fault diagnosis module, a reconfiguration mechanism module and an adjustable controller module. The fault diagnosis module is used to detect the PEMFC current fault type. According to the diagnosis results, the reconfiguration mechanism determines which backup controller to be undertaken. The adjustable controller integrated to the fault tolerance control approach is a nonlinear controller based on a feedback linearization method. Feedback linearization is a well-known approach applied to control nonlinear systems [33]. The controller has high robustness against PEMFC model uncertainties and low computational time, which is a suitable candidate to be used as reconfigurable controller module.

The paper is organized as follows: In Section 2, three lumped-parameter models are respectively established to reproduce the PEMFC normal, membrane drying and flooding conditions. In Section 3, the detailed fault-tolerant control strategy for the PEMFC system is proposed. Section 4 shows the simulation results, which verify the effectiveness of the proposed fault-tolerant control system. Finally, some concluding remarks are made in Section 5.

2. PEMFC models

To analyze the fault reasons and design fault-tolerant controllers for the PEMFC, three lumped-parameter models are respectively built to reproduce the PEMFC normal operation, membrane drying operation and flooding condition. The following assumptions are list to develop the PEMFC dynamic models:

- In the anode, fuel includes H_2 and H_2O. In the cathode, air contains O_2, $N_2$and H_2O.
- Both the fuel and air are the ideal gas.
- The electrochemistry reaction is steady.
- Each fuel cell in the PEMFC stack operates identically.
- No liquid water enters the cell. However, liquid water may exist at the cathode outlet.
- The temperature is uniform over the whole length of the stack.
- The coolant outlet temperature equals to the temperature of the PEMFC stack.

2.1. Normal operation model

2.1.1. Cathode model

The dynamics of the partial pressure of oxygen, nitrogen and water in PEMFC cathode are respectively given by Ref. [15]:

$$\frac{\mathrm{d}p_{O_2}}{\mathrm{d}t} = \frac{R_{O_2}T}{V_{ca}}\left(W_{O_2,in} - W_{O_2,rea} - W_{O_2,out}\right) \tag{1}$$

$$\frac{\mathrm{d}p_{N_2}}{\mathrm{d}t} = \frac{R_{N_2}T}{V_{ca}}\left(W_{N_2,in} - W_{N_2,out}\right) \tag{2}$$

$$\frac{\mathrm{d}p_{w,ca}}{\mathrm{d}t} = \frac{R_v T}{V_{ca}}\left(W_{v,ca,in} - W_{v,ca,out} + W_{v,mbr} + W_{v,gen}\right) \tag{3}$$

To humidify the incoming dry air, a humidifier is used in the cathode side in this paper. Thus, the cathode inlet oxygen, nitrogen and water flowrate in Eqs. (1)–(3) can be respectively calculated as follows [15,37]:

$$W_{O_2,in} = W_{O_2,hm,out} = \frac{x_{O_2}M_{O_2}k_{hm,in}\cdot\left(p_{a,in} - p_{O_2} - p_{N_2} - p_{v,ca}\right)}{\left(x_{O_2}M_{O_2} + x_{N_2}M_{N_2}\right)\cdot(1+\Omega_{atm})} \tag{4}$$

$$W_{N_2,in} = W_{N_2,hm,out} = \frac{x_{N_2}M_{N_2}k_{hm,in}\cdot\left(p_{a,in} - p_{O_2} - p_{N_2} - p_{v,ca}\right)}{\left(x_{O_2}M_{O_2} + x_{N_2}M_{N_2}\right)\cdot(1+\Omega_{atm})} \tag{5}$$

$$W_{v,ca,in} = W_{v,hm,out} = \frac{\Omega_{atm}k_{hm,in}\cdot\left(p_{a,in} - p_{O_2} - p_{N_2} - p_{v,ca}\right)}{1+\Omega_{atm}} + W_{v,inj} \tag{6}$$

where, $W_{v,inj}$ is the injected water vapor flowrate in the humidifier, and Ω_{atm} is atmospheric humidity ratio expressed by Ref. [15]: