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Fault tolerance control of SOFC systems based on nonlinear model predictive control

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ABSTRACT

Heat management and load tracking are two crucial tasks for solid oxide fuel cell (SOFC) systems development. In literature, plenty of temperature controllers and load tracking controllers have been successfully designed for SOFC systems. However, previous researches are limited to control design in the case of SOFC normal conditions. For a SOFC system, faults can occur on any parts at any time, thus a controller with a specific design must be used. In this work a new control strategy that tolerates the SOFC system faults is proposed, which includes a fault diagnosis module, a decision-making part and four backup controllers. The fault diagnosis part is used to classify the SOFC system current faults (normal, fuel leakage fault, air compressor fault, or both fuel leakage and air compressor faults). Based on the diagnosis results, the decision-making part is designed to select the appropriate backup controller. Four nonlinear model predictive controllers based on back propagation (BP) neural networks are respectively built to follow loads and maintain appropriate temperatures in the case of fuel leakage fault, air compressor fault, both fuel leakage and air compressor faults, and SOFC normal condition. The results show that the proposed fault tolerance control strategy can track the voltage and make the SOFC temperature steady near the enactment value in working in faulty conditions, which may result in both lifetime and performance improvement for the SOFC systems.

Introduction

Solid oxide fuel cell (SOFC) is an electrochemical device which can convert chemical energy into electricity. Due to its fuel flexibility, lower emissions and high efficiency, SOFC is considered as a promising generating plant. For SOFC development, thermal management is an important control task, because high operating temperatures may lead to thermal gradient and local hot spots [1]. Moreover, load transients often involve significant peaks in power relative to the steady-state load [2]. Thus, load tracking is another important control task.

In recent years, diverse temperature controllers have been developed to ensure the SOFC system a proper operating temperature. In Refs. [3,4], a typical feedback proportional-integral-derivative (PID) controller was implemented to track the SOFC temperature. A model predictive control method was developed to predict the SOFC temperature in Refs. [5,6]. In Refs. [7,8], $H\infty$ and LMI technique were employed to keep the SOFC temperature stable. In Ref. [9], a nonlinear sliding mode observer was designed to estimate the temperature distribution in a hydrogen fed SOFC stack. In order to track the load variation, plenty of voltage or power controllers have been proposed. In Refs. [10–12], the $H\infty$ control technique was applied to keep the

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SOFC output follow the load variations. In Refs. [3,13–15], the PID controller was designed to study the SOFC load tracking ability. The model predictive control was developed to track the SOFC output in Refs. [16,17]. The above studies can effectively regulate the temperature into the normal range and track the SOFC load. However, these controllers do not take into account the impact of the faulty conditions on the SOFC system instantaneous performance, which are limited to control design in the case of SOFC normal conditions.

In SOFC real operations, faults may occur on any parts at any time, such as fuel leakage fault, air compressor fault or sensors failures etc. These malfunctions may lead to performance losses, irreversible degradation and even system failure [18]. In order to improve the stability and durability for the SOFC system, plenty of fault diagnosis methods have been proposed. These methods can be divided into two main classes: model-based diagnosis [19–24] and non-model-based diagnosis, such as principal component analysis method [25], fault-tree algorithms [26–28], artificial neural network method [29], or wavelet transform approach [30]. Barelli et al. [18] made an overview of the references related to the SOFC diagnosis methods.

Plenty of fault diagnosis strategies and control methods have been proposed for the SOFC system, however, combining fault diagnosis with control technique is still lacking. Sun et al. [31,32] presented a fault tolerance control strategy to control the SOFC temperature and power. However, this controller was designed only for a SOFC stack. It is not suitable for a complete SOFC system that involves many ancillaries. Moreover, the proposed reconfiguration controller was designed based on the linearization model of the SOFC stack. Actually, the SOFC is a severe nonlinear system, which restricts the applicability of the proposed strategy.

To overcome the above limitation, a fault tolerant control strategy for a complete SOFC system is proposed, which consists of a fault diagnosis, a decision-making part and four backup controllers. A model-based classifier is used as the fault diagnosis tool to detect the current fault type of the SOFC system (air compressor fault, fuel leakage fault, both air compressor and fuel leakage faults, or normal). On the basis of the diagnosis result, the decision-making part selects the appropriate backup controller to track the SOFC system voltage and keep the SOFC temperature steady. A nonlinear model predictive control strategy based on back propagation (BP) neural networks is employed to design the four backup controllers in the case of SOFC normal, fuel leakage, air compressor faults, and both fuel leakage and air compressor faults. Predictive control is a model-based control strategy, which usually consists of a predictive model and an optimized controller [33]. Neural network is an effective tool to identify the dynamics of the nonlinear system, because of its “universal approximator” property [34]. Thus, in this work, several BP neural networks in an interative method are firstly employed as the predictive model to predict the future response of the SOFC system based on past observations. Then two parallel BP neural networks are developed as the optimizer to control the SOFC temperature and voltage. By solving an optimization problem at each sampling interval, the optimal control action can be calculated to maintain the output of SOFC system close to the reference.

The paper hereafter is formed as below. “SOFC system model” Section builds the SOFC system models under the various fault types. In “The proposed tolerance control strategy for the SOFC system” Section, the fault tolerance control framework of the SOFC system is presented. The reconfigurable control algorithm based on the nonlinear model predictive controller is illustrated in “Reconfigurable control algorithm for the SOFC system” Section. In “Results” Section, the fault tolerance control results from the concerned SOFC system are given. “Conclusions” Section draws the conclusion.

SOFC system model

A typical SOFC system is developed, which is given in Fig. 1 [5]. The SOFC system includes an air compressor, an air preheater, a fuel reformer, a SOFC stack and a burner. It is given that faults can occur in any parts of the SOFC system. In the view of system design, it is not necessary and possible to detect the exact locations for all minor faults. Thus, the following two faults are taken into account in a subunit level of the SOFC system:

1) Fuel leakage between the reformer exit and the SOFC stack entrance. For high diffusivity of hydrogen molecule and small size, the hydrogen content at the reformer exit is very high. Thus, hydrogen leakage is probable to occur [28].
2) Air blower fault induced by an increase in its mechanical losses.

In order to obtain suitable data for the training and validation of the BP neural network predictive control, four lumped-parameter models are respectively built to reproduce the SOFC normal, fuel leakage, air compressor malfunction, and both fuel leakage and air compressor faults. The following assumptions are listed to develop the dynamic models for the SOFC system:

- The inlet fuel includes CH_4 and H_2O, and steam to carbon ratio equals 2.5.
- The inlet air contains O_2 and N_2.
- Both the fuel and air are the ideal gas.
- The electrochemistry reaction is steady.
- Each fuel cell in the SOFC stack operates identically.
- H_2 and CO is completely combusted in the burner.

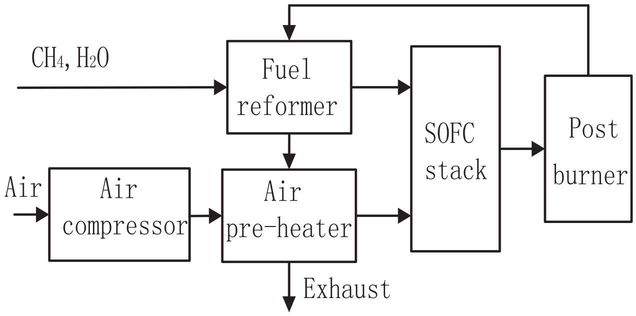

Fig. 1 – Structure diagram of the SOFC system.

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