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Robust fault diagnosis of proton exchange membrane fuel cells using a Takagi-Sugeno interval observer approach

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ABSTRACT

In this paper, the problem of robust fault diagnosis of proton exchange membrane (PEM) fuel cells is addressed by introducing the Takagi-Sugeno (TS) interval observers that consider uncertainty in a bounded context, adapting TS observers to the so-called interval approach. Design conditions for the TS interval observer based on regional pole placement are also introduced to guarantee the fault detection and isolation (FDI) performance. The fault detection test is based on checking the consistency between the measurements and the output estimations provided by the TS observers. In presence of bounded uncertainty, this check relies on determining if all the measurements lie inside their corresponding estimated interval bounds. When a fault is detected, the measurements that are inconsistent with their corresponding estimations are annotated and a fault isolation procedure is triggered. By using the theoretical fault signature matrix (FSM), which summarizes the effects of the different faults on the available residuals, the fault is isolated by means of a logic reasoning that takes into account the bounded uncertainty, and if the number of candidate faults is more than one, a correlation analysis is used to obtain the most likely fault candidate. Finally, the proposed approach is tested using a PEM fuel cell case study proposed in the literature.

Introduction

In the last years, major efforts to reduce greenhouse effects and pollution have increased the demand for environmentally friendlier energy sources [1]. Fuel cells have been pointed out as a promising alternative way for an energy source in the future, not only because they are considered a zero-emission power source, but also because

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they are very quite, and reduce noise pollution. Their energy density makes them specially suitable for embedded generation systems in transport applications. Proton exchange membrane fuel cells (PEMFC) are electrochemical devices in which the energy of a reaction between a fuel, the hydrogen, and an oxidant, the oxygen, is directly and continuously converted into electrical energy, obtaining water as a subproduct [2]. Many control strategies for PEMFC have been proposed in the recent literature, e.g. optimal control [3], model predictive control [4] and sliding mode control [5].

However, fuel cell technology is still too expensive to be accessible to a mass market, and there are still considerable difficulties to overcome. One of the main drawbacks of fuel cell systems is related to the stack lifetime and reliability when working at strongly changing charge conditions, like those that could be usually found in transport applications. Several papers have analyzed the PEMFC durability taking into account the phenomena that could affect the PEMFC lifetime [6–8], e.g. catalyst degradation, fuel starvation or inadequate water management [9–11]. To overcome these drawbacks, adequate fault detection and isolation (FDI) and fault-tolerant control (FTC) strategies are needed to avoid failure modes which could compromise the stack reliability and integrity. Real-time fault diagnosis (detection and isolation) can provide valuable information either for monitoring PEMFC operation, allowing to reconfigure/accommodate the control loop whenever any malfunction is reported, or to suggest preventive maintenance actions, to extend the lifetime of the system and thereby avoiding future damage in the equipment.

In Ref. [12], fault diagnosis of PEMFC is reviewed with a special emphasis on model-based methods. Fuel cells are complex and strongly *non-linear* systems in which continuously varying parameters are difficult to identify, even for static operation modes. Different authors have chosen different approaches for fuel cell system modeling. Electric equivalent models [13], state space models [14,15] and bond graph representation models [16] are the most representative approaches. Even if these models can represent fuel cell behavior at some operating conditions, their application to fault diagnosis is not so straightforward and, moreover, most of them are related just to the stack and not to the overall system.

Recently, the complex and non-linear dynamics of the power generation systems based on fuel cell technology, described in detail in Ref. [14], led to the use of linear models that include parameters varying with the operating point (known as linear parameter varying or LPV models) not only for advanced control [17] but also for model-based fault diagnosis [18] purposes. The use of Takagi-Sugeno (TS) models [19] is an alternative to LPV models as a linear-like modeling framework that allows extending control [20] and FDI methods to non-linear systems [21]. Thus, this paper will consider TS models and observers for FDI in PEM fuel cells. In the literature, the use of the TS has been widely considered for FDI (see, e.g. Refs. [21,22]) and fault estimation/FTC (see e.g. Refs. [23,24]). However, due to the presence of parametric uncertainties in the TS model, the design of a conventional observer that converges to the exact value of the state is complicated [25]. In this situation, an interval estimation is still possible, and an observer that evaluates the set of admissible values for the state at each time instant can be designed [25–29].

The main contribution of this paper is to address the problem of robust fault diagnosis of PEM fuel cells by introducing the TS interval observers that consider uncertainty in a bounded context, adapting TS observers to the so-called interval approach. Design conditions for the TS interval observer based on regional pole placement are also introduced to guarantee the FDI performance. A bank of observers is designed by applying the structural analysis [30] to the PEMFC model considering the set of available sensors. The fault detection test is based on checking the full consistency between the measurements and the output estimations provided by the TS interval observers. In presence of bounded uncertainty, this check relies on determining if all the measurements lie inside their corresponding estimated interval bounds. In the case a fault is detected, the measurements that are inconsistent with their corresponding estimations are annotated and a fault isolation procedure is triggered. By using the theoretical fault signature matrix (FSM), the fault is isolated by means of a logic reasoning that takes into account the presence of bounded uncertainty, and a posterior correlation analysis provides the most likely fault candidate. Finally, the proposed approach is tested using a well known PEMFC case study proposed in the literature in Ref. [14] by deriving an interval TS model and observer.

Modeling of the PEMFC

Description

The fault diagnosis approach proposed in this paper is tested on a typical PEMFC system (see Fig. 1) based on the model provided in Ref. [2].

The fuel cell, in response to a current demand by an electrical load, consumes oxygen and hydrogen and generates water and heat. The hydrogen is provided by the hydrogen supply system, whose main components are a pressurized hydrogen tank and a supply servo valve that allows controlling the hydrogen flow or pressure. The air supply system, consisting mainly of a compressor driven by an electric motor, provides the air flow. The control of the hydrogen and air supply systems aims at maintaining the required partial pressures of the hydrogen and air entering into the anode and the cathode of the stack, respectively. Additionally, since the compressor provides air at a high temperature due to the increased pressure, the cooling system is used to reduce the temperature of the air entering into the stack in order to prevent the fuel cell membrane from damaging. Finally, a humidifier acts on the cathode path to prevent membrane damage due to dehydration.

The main variables involved in the PEMFC system operation are listed in Table 1.

Following other works in the literature, e.g. Ref. [31], six variables are assumed to be measured: