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Robust fault tolerant control of DFIG wind energy systems with unknown inputs

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ABSTRACT

This paper proposes a Fuzzy Dedicated Observers (FDOS) method using a Nonlinear Unknown Input Fuzzy Observer (UIFO) with a Fuzzy Scheduler Fault Tolerant Control (FSFTC) algorithm for fuzzy Takagi-Sugeno (TS) systems subject to sensor faults, parametric uncertainties, and time varying unknown inputs. FDOS provide residuals for detection and isolation of sensor faults which can affect a TS model. The TS fuzzy model is adopted for fuzzy modeling of the uncertain nonlinear system and establishing fuzzy state observers. The concept of Parallel Distributed Compensation (PDC) is employed to design FSFTC and fuzzy observers from the TS fuzzy models. TS fuzzy systems are classified into three families based on the input matrices and a FSFTC synthesis procedure is given for each family. In each family, sufficient conditions are derived for robust stabilization, in the sense of Taylor series stability and Lyapunov method, for the TS fuzzy system with parametric uncertainties, sensor faults, and unknown inputs. The sufficient conditions are formulated in the format of Linear Matrix Inequalities (LMIs). The effectiveness of the proposed controller design methodology is finally demonstrated through a wind energy system with Doubly Fed Induction Generators (DFIG) to illustrate the effectiveness of the proposed method.

1. Introduction

Nonlinearity and uncertainty are difficult problems in controller design for real systems because there is no systematic way to find a necessary and sufficient stability condition to guarantee good robustness and performance. Wind turbines are complex nonlinear mechanical systems exposed to uncontrolled wind profiles which makes turbine controller design a challenging task [1]. Takagi-Sugeno (TS) fuzzy logic control is an effective way to design nonlinear control systems in the presence of plant parameters which incomplete known [2]. The stability of fuzzy systems formed by a fuzzy plant model and a fuzzy controller has recently been investigated. Various stability conditions have been obtained through the employment of Lyapunov stability theory [3,4], fuzzy gain-scheduling controllers [5–9], switching controllers [10] and other methods [11–13]. During the last decades, most of researches have been focused on the analysis and control design for wind turbine with parametric uncertainties [14–22]. The problem of power regulation for fixed-pitch variable-speed Wind Energy Conversion System (WECS) with parametric uncertainties is presented in [14]. Ref. [15] presents a fuzzy sliding mode control object with parameter uncertainties and disturbances. Variable-pitch wind turbine with uncertain parameter based on Linear Matrix Inequalities (LMIs) is presented in Ref. [16]. Multivariable frequency domain techniques as a tool for controller design and dynamic analysis of a WECS, and design the robust model based controllers for such systems are presented in Ref. [17]. Ref. [18] concerns power regulation of variable-speed WECS subject to wind disturbances and parameter uncertainties by sliding control in the minimum phase region. Comparing between PI and pitch controller's variable-pitch wind turbine is presented in Ref. [19]. A fuzzy controller is also shown to permit an increase in captured wind energy in both high and low wind speeds in Ref. [20,21]. In Ref. [22] a design methodology for TS fuzzy models is presented. This design methodology is based on fuzzy clustering methods for partitioning the input–output space combined with Genetic Algorithms (GA) and recursive Least-Squares (LS) optimization methods for model parameter adaptation. Doubly Fed Induction Generators (DFIG) have become a widely used generator type in wind energy conversion. Considerable research has been done on the modeling and control of wind turbines with DFIG [23–27], since it features a simple structure, high-energy efficiency, reliable operation, and high power density. However, the DFIG drive system is a nonlinear system which is characterized by multiple variables and a strong coupling with profuse dynamics.

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In addition, the controller design will become more complex if the uncertain nonlinear system is subject to sensor faults. Fault Tolerant Control (FTC) in WECS has been studied for the last two decades [28–35]. In Ref. [28] design robust fault tolerant controller based on a two-frequency-loop. The low-frequency-loop adopts PI steady-state optimization control strategy, and the high-frequency-loop adopts Robust Fault Tolerant Control (RFTC) approach, thus ensuring the actuator part of the systems in the case of failure to normal operation. Ref. [29] presents active fault tolerant control for nonlinear systems with sensor faults and a method for designing robust controllers to stabilize sensor fault nonlinear systems. In Ref. [30–32] the fault tolerant control strategy for wind energy conversion systems has been well developed and extensively applied to efficiently deal with the problems of robust stabilization and disturbance rejection. A Fault Detection and Isolation (FDI) based scheme is presented in Ref. [33,34], to detect and accommodate faults in wind turbines. Unknown input observer design for general nonlinear systems is still largely an open problem, and thus nonlinear unknown input observer based on fault diagnosis remains as an area for further research [35–38].

Therefore, in this paper, Fuzzy Scheduler Fault Tolerant Control (FSFTC) is proposed to tackle multivariable nonlinear systems subject to large parameter uncertainties within given ranges, sensor faults and time varying unknown inputs, a FSFTC has been realized based on the analysis results of the Robust Fuzzy Control (RFC) [39]. FSFTC has a number of RFC controllers embedded inside, and the control signal is obtained based on these RFC fuzzy controllers outputs. The design is based on an augmented TS fuzzy plant model which is formed by the original TS fuzzy plant model and a fuzzy uncertainty regenerator. FSFTC is effectively adaptive controllers and changes its parameters as the membership function values change with the uncertain plant parameters.

For a given nonlinear plant [20], the number of RFC [39] that have to be designed under the fuzzy scheduler approach is fixed. To solve the control problem of nonlinear fuzzy control systems subject to large parameter uncertainties, corner fuzzy controllers for all the corner fuzzy systems have to be designed first. These corner fuzzy controllers can only provide acceptable control signals for the corresponding corner fuzzy control systems but not the entire specified parameter space. Therefore, when the system parameters deviate from a corner grid-point, a fuzzy scheduler is proposed to deduce the control signal by considering all the corner fuzzy controllers. The stability and robustness of the fuzzy scheduled system will be investigated. This proposed scheme is based on the Fuzzy Dedicated Observers (FDOS) method using a Nonlinear Unknown Input Fuzzy Observer (UIFO). Each one of the FDOS is dedicated to each output of the multi-sensors to generate a set of residual signals which, are determined by the difference between the systems measurements and the estimated output of the observers based on Ref. [40–42]. By the reconfiguration mechanism (Decision and Switcher) of the residuals, the sensor faults can be detected and isolated. Utilizing a Parallel Distributed Compensation (PDC) structure, a method of analyzing the system in terms of LMIs is obtained by applying fuzzy Taylor series expansion and Lyapunov method to fuzzy system sensor faults. The TS fuzzy systems are classified into three families based on the input matrices and a unique FSFTC synthesis procedure is developed for each family. A WECS with DFIG is presented to illustrate and verify the results of this paper.

This paper is organized as follows. Section 2 provides the proposed FSFTC scheme, TS fuzzy model FDOS and UIFO. Section 3 shows the stability and robustness conditions for the proposed algorithm followed by the calculation of state FSFTC, FDOS and UIFO gains. Section 4 shows WECS model system with DFIG. Simulation and results are shown in Section 5 and conclusions are given in Section 6.

2. The proposed FSFTC scheme, TS fuzzy plant model, FDOS and UIFO

In this section, the TS fuzzy plant model subject to parameter uncertainties, sensor faults, unknown inputs and wind disturbance will be expressed as a weighted sum of a number of fuzzy systems. An augmented TS fuzzy plant model is formed by adding a fuzzy uncertainty regenerator.

2.1. The structure of the proposed FTC scheme

The proposed scheme, illustrated in Fig. 1, is based on observers which detect and isolate the sensor faults and an unknown input observer which estimates the unknown input and reconstructs the state of the WECS from a healthy estimate. Each one of the FDOS is driven by all sensed outputs with the exception of the particular output that is to be estimated in order to generate residual signals corresponding to the difference between measured and estimated variables. The estimated unknown input from the UIFO is fed to the FDOS. Through the decision and switcher mechanism, detecting and identifying the faulty sensor is possible. Finally, by using a switcher, selecting the healthy observer for reconstructing the controller input is enabled. In our study the proposed robust fault tolerant controller is based on one observer (observer 6). It is assumed that at any given time only one sensor fails at most.

2.2. TS fuzzy model with unknown input, parameter uncertainties and sensor faults

The TS fuzzy systems can be classified into three families based on the diversity of their input matrices.

First, to consider is the family of TS fuzzy systems with the input matrices on a one-dimensional cone:

$$B_1/\alpha_1 = B_2/\alpha_2 = \ldots = B_p/\alpha_p = B \tag{1}$$

where $\alpha_1, \ldots, \alpha_p > 0$ and $B \in k^{nxm}$. Consider the continuous fuzzy dynamic model given in Ref. [10,39]. The *i*th rule of this fuzzy model is given by:

Plant Rule i: IF $q_1(t)$ is N_{1i} AND … AND $q_\psi(t)$ is $N_{\psi i}$

$$\begin{aligned} \text{Then} \quad \dot{x}(t) &= (A_i + \Delta A_i)x(t) + \alpha_i B u(t) \\ y(t) &= C_i x(t) \end{aligned} \tag{2}$$

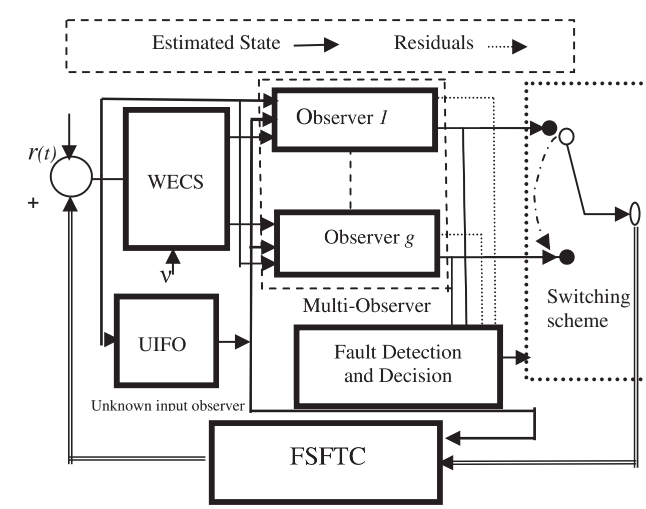

Fig. 1. Block diagram of the proposed scheme.