Fuzzy Fault Tolerant Control For Wind Energy System Subject to Parameters Uncertainties and Unknown Inputs

E. Kamal, A. Aitouche, *Member, IEEE* , R. Ghorbani and M. Bayart

***Abstract*--This paper addresses stability analysis for a class of nonlinear systems with sensor faults and unknown inputs in the presence of parameter uncertainties and a method for designing robust fuzzy Fault Tolerant Controllers (FTC) to stabilize the uncertain nonlinear faulty systems. New stability conditions for a generalized class of uncertain faulty systems are derived from robust FTC control techniques such as Linear Matrix Inequalities (LMIs) and Linear Matrix Equations (LMEs). The derived stability conditions are used to analyze the stability of TS fuzzy control systems with parameters uncertainties, sensor faults and unknown inputs which can be regarded as a generalized class of uncertain nonlinear faulty systems. The design method employs the so-called Parallel Distributed Compensation (PDC). Important issues for the stability analysis and design are remarked. Finally, Wind Energy Systems (WES) with a Doubly-Fed Induction Generator (DFIG) example is illustrated to show the effectiveness of the proposed design method.**

***Index Terms*—FTC, FDI, TS Fuzzy Controller, Fuzzy Observer, LMIs, Sensor Faults, parameter uncertainties, TS Fuzzy Model, WES.**

I. INTRODUCTION

FAULT Tolerant Control (FTC) is one of the lines of research that have received a lot of interest in the last decades. According to [1], FTC allows maintaining the current performance close to desirable one and preserve stability conditions in the presence of component and/or instrument faults. Some researchers pay more attention to fault tolerant control approach for system with sensor and/or unknown inputs and parametric uncertainties [2]-[10].

In recent years, some authors considered nonlinear unknown input observer-based fault detection and isolation (FDI) methods for a nonlinear systems. In [11], a full-order nonlinear unknown input observer design problem is proposed; on the basis of this, fault detection and isolation problem is studied [12], one advantage is that a systematic nonlinear unknown input observer design way is provided in terms of Linear Matrix Inequalities (LMIs)-based existence conditions for nonlinear unknown input observer. A robust nonlinear unknown input observer is designed to detect and isolate parameter fault when disturbances and noises occur simultaneously [13].

In this paper the robust fuzzy FTC problem for uncertain nonlinear systems in the sensor faults and unknown inputs is addressed and the state variables are unavailable for measurement via "Takagi-Sugeno" (TS) fuzzy models. TS fuzzy model system with parametric uncertainties, sensor faults and unknown inputs is adopted for modeling the nonlinear system and establishing fuzzy observer. Sufficient conditions are derived for robust stabilization in the sense of Taylor series and are formulated in the format of Linear Matrix Inequalities (LMIs). In addition, we revisit the problem of robust FTC state-feedback control for a class of uncertain nonlinear faulty systems via TS fuzzy models. In this paper, the approach of [22] is extended to the case of a class of uncertain nonlinear systems that are driven by sensor faults and unknown inputs. The LMIs and Linear Matrix Equations (LMEs) are used in the design of FTC controller, multi-observers and nonlinear unknown observers which, for sensor fault detection and isolation, unknown inputs and parameter uncertainties. In the next section, we present the model and the corresponding multi-observers and unknown-input observer. Then we will show how these observers can be used to accomplish single sensor fault detection and isolation and compensate the unknown inputs. A Wind Energy Systems (WES) with Doubly-Fed Induction Generator (DFIG) is presented to illustrate and verify the results of this paper.

The rest of this paper is structured as follows: TS fuzzy model and the structure of the fuzzy observers are presented in section II. Section III shows the proposed FTC controller and stability analysis. In Section IV, the model of the WES with Doubly-Fed Induction Generator (DFIG) and its TS fuzzy description and Simulation example are presented. In Section V, conclusions are presented.

E. Kamal is with LAGIS, Lille University Nord of France, Villeneuve d'Ascq, Polytech'Lille, France (e-mail: elkateb.kamal@gmail.com).
A. Aitouche is with LAGIS Laboratory, Lille University Nord of France, HEI, Lille, France (e-mail: abdel.aitouch@hei.fr).
R. Ghorbani is with Mechanical Engineering, University of Hawaii, Manoa, 2540 Dole St. - Holmes Hall 201, Honolulu HI, (email: rezeg@hawaii.edu).
M. Bayart is with LAGIS, Lille University Nord of France, Villeneuve d'Ascq, Polytech'Lille, France (e-mail: mireile.bayrt@univ-lille1.fr).

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II. TS FUZZY PLANT MODEL AND TS FUZZY OBSERVERS

A. *TS Fuzzy Plant Model with Unknown Inputs and Sensor Faults*

The TS fuzzy rules for the uncertain nonlinear system with unknown inputs and sensor faults are given by [14], [15].

Rule *i:* IF $Z_1(t)$ is M_{1i} AND …AND $Z_k(t)$ is M_{ki}

Then $\dot{x}(t) = (A_i + \Delta A_i)\, x(t) + B_i u(t) + \overline{D}_i d(t)$

$$y(t) = C_i\,(I + F)x(t) \tag{1}$$

where $M_{\alpha i}$ is a fuzzy term of rule *i*, $i = 1, ...,p; \alpha=1,2,...,k$, *p* is the number of rules, $Z(t)=[Z_1(t),...,Z_k(t)]$ are the premise variables and are not affected by the fault, $x(t)\epsilon\kappa^{nx1}$ is the state vector, $u(t)\epsilon\kappa^{mx1}$ is the control input vector, $d(t)\epsilon\kappa^{qx1}$ contains the unknown inputs ($q<n$), $y(t)\epsilon\kappa^{gx1}$ is the output vector, $A_i\epsilon\kappa^{nxn}$, and $B_i\epsilon\kappa^{nxm}$ are the system matrix and input matrix, respectively, $\Delta A_i\epsilon\kappa^{nxn}$ is the parameter uncertainties of system matrix, $C_i\epsilon\kappa^{gxn}$ is the output matrix, $\overline{D}_i\,\epsilon\kappa^{nxq}$, $\overline{D}_i = B_i D_i$, and $D_i\epsilon\kappa^{mxq}$ are known matrices of unknown inputs, *I* is the identity matrix, F=diag$(F_1,F_2,...,F_g)$ are faults which are modelled as proportional signals to sensor outputs, *g* is the number of sensors, and $F_a=\alpha_a$ if the sensor *a* is faulty ($a=1,2,...,g$), where $-0.1<\alpha_a<0.1$. The inferred system states are governed by:

$$\dot{x}(t) = \sum_{i=1}^{p}\mu_i(Z(t))[\,(A_i + \Delta A_i)x(t) + B_i u(t) + \overline{D}_i d(t)\,]$$

$$y(t) = \sum_{i=1}^{p}\mu_i(Z(t))(I + F)C_i x(t) \tag{2}$$

$$\text{where } \mu_i(Z(t)) = \frac{h_i(Z(t))}{\sum\limits_{i=1}^{p} h_i(Z(t))} \qquad h_i(Z(t)) = \prod_{\alpha=1}^{k} M_\alpha^i(Z_\alpha(t)) \tag{3}$$

Some basic properties of $h_i(Z(t))$ are:

$$h_i(Z(t)) \geq 0\,,\ \sum_{i=1}^{p} h_i(Z(t)) \geq 0 \quad i = 1,2,....,p$$

It is clear that

$$0 \leq \mu_i(Z(t)) \leq 1,\ \sum_{i=1}^{p}\mu_i(Z(t)) = 1 \quad \forall i = 1,2,....,p \tag{4}$$

B. *Proportional- Unknown and Multi-Observers*

In this sub-section, we present the unknown nonlinear fuzzy observer design methodologies involving unknown input estimation for TS fuzzy models and the dedicated multi-observers:

First, the fuzzy state unknown inputs observer for TS fuzzy model with parametric uncertainties unknown inputs and sensor faults (1) is formulated as the following [13] and writing μ_i (Z(t)) as μ_i;

$$\dot{\hat{x}}_u(t) = \sum_{i=1}^{p}\mu_i\,[A_i\,\hat{x}_u(t) + B_i u(t) + K_i(y(t)\text{-}\hat{y}_u(t)) + \overline{D}_i\hat{d}(t)]$$

$$\dot{\hat{d}}(t) = \sum_{i=1}^{p}\mu_i L_i(y\text{-}\hat{y}_u) = \sum_{i=1}^{p}\mu_i L_i\tilde{y}$$

$$\hat{y}_u(t) = \sum_{i=1}^{p}\mu_i C_i\hat{x}_u(t) \tag{5}$$

where $K_i\ (1,2,...,p)$ are observation error matrices, L_i are their corresponding integral gains to be determined.

Second, the fuzzy state of dedicated observers is considered as follows [16]:

$$\dot{\hat{x}}_D(t) = \sum_{i=1}^{p}\mu_i[A_i\hat{x}_D(t) + B_i u(t) + N_i(y(t)\text{-}\hat{y}_D(t)) + \overline{\mathrm{D}}_\mathrm{i}\hat{\mathrm{d}}(\mathrm{t})]$$

$$\hat{y}_D(t) = \sum_{i=1}^{p}\mu_i C_i\hat{x}_D(t) \tag{6}$$

where $N_i\epsilon\kappa^{nx1}$ is constant observer gain to be determined.

III. CONTROL DESIGN AND STABILITY ANALYSIS

In this section, a fault-tolerant controller based on TS fuzzy model is proposed for a class of uncertain nonlinear systems with unknown input and unexpected sensors faults.

A. *TS Fuzzy FTC Controller*

The standard TS fuzzy controller consists of the set of fuzzy rules with linear consequent that describe controller in a local areas *j*. The concept of Parallel Distributed Compensation (PDC) [14] is employed to design the fuzzy controller. For our purpose we suppose following form:

Rule *j:* IF $Z_1(t)$ is M_{1j} AND …AND $Z_k(t)$ is M_{kj}

$$\text{Then} \quad u(t) = -G_j x(t) - D_j\hat{d}(t) + r(t) \tag{7}$$

where $G_j\epsilon\kappa^{mxn}$ are feedback gain vectors of rule *j*, , $j = 1, ...,c;$ *c* is the number of rules, and *r(t)* is the reference input. Then, the final output of the fuzzy controller is

$$u(t) = \sum_{j=1}^{c}\mu_j[\,-G_j\ x(t) - D_j\hat{d}(t) + r(t)] \tag{8}$$

If some state variables have to be estimated by a fuzzy observer (6), then the fuzzy FTC output (8) is computed in the following way:

$$u(t) = \sum_{j=1}^{c}\mu_j[\,-G_j\ \hat{x}_D(t) - D_j\hat{d}(t) + r(t)\,] \tag{9}$$

B. *The Proposed FTC Algorithm and Stability Analysis*

The aim of the observer is to eliminate estimation error as fast as possible. Estimation errors is defined as

$$e_1(t) = x(t)\text{-}\hat{x}_D(t) \tag{10}$$

$$e_2(t) = x(t)\text{-}\hat{x}_u(t) \tag{11}$$

$$\tilde{d}(t) = d(t)\text{-}\hat{d}(t) \tag{12}$$

$$R_{res}(t) = y(t)\text{-}\hat{y}_u(t) = \sum_{i=1}^{p}\mu_i C_i e_1(t) \tag{13}$$

where R_{res} is the residuals between the actual outputs and the estimated output. From (2), (5), (6), (9), (10) and (11), we can obtain the fuzzy control system of the state and the errors,

$$\dot{x}(t) = \sum_{i=1}^{p}\sum_{j=1}^{c}\mu_i\mu_j[((A_i + \Delta A_i) - B_i G_j)x(t) + B_i G_j e_1(t) + \overline{D}_j\tilde{d}(t) + B_i r(t)] \tag{14}$$

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$$\dot{e}_1(t) = \sum_{i=1}^{p}\sum_{j=1}^{c}\mu_i\mu_j[(\Delta A_i - NFC_j)x(t) + (A_i - N_iC_j)e_1(t) + \overline{D}_i\tilde{d}(t)] \quad (15)$$

$$\dot{e}_2(t) = \sum_{i=1}^{p}\sum_{j=1}^{c}\mu_i\mu_j[(\Delta A_i - K_iFC_j)x(t) + (A_i - K_iC_j)e_2(t) + \overline{D}_i\tilde{d}(t)] \quad (16)$$

if $d(t)$ is constant, then $\dot{d}(t) = 0$, The derivative of $\dot{\tilde{d}}(t)$ can be written as,

$$\dot{\tilde{d}}(t) = \dot{d}(t) - \dot{\hat{d}}(t) = -\dot{\hat{d}}(t) = -\sum_{i=1}^{p}\mu_i[L_iFC_ix + L_iC_ie_2(t)] \quad (17)$$

Combining (14)-(17) yields the following augmented fuzzy system.

$$\dot{X}(t) = (H_{ij} + \Delta H_{ij})X(t) + S_ir(t) \quad (18)$$

with $X(t) = \begin{bmatrix} x(t) \\ e_1(t) \\ e_2(t) \\ \tilde{d}(t) \end{bmatrix}$, $S_i = \begin{bmatrix} B_i \\ 0 \\ 0 \\ 0 \end{bmatrix}$, $\Delta H_{ij} = \begin{bmatrix} \Delta A_i & 0 & 0 & 0 \\ (\Delta A_i - NFC_j) & 0 & 0 & 0 \\ (\Delta A_i - K_iFC_j) & 0 & 0 & 0 \\ L_iFC_i & 0 & 0 & 0 \end{bmatrix}$

$$H_{ij} = \begin{bmatrix} (A_i - B_iG_j) & B_iG_j & 0 & \overline{D}_j \\ 0 & (A_i - N_iC_j) & 0 & \overline{D}_i \\ 0 & 0 & (A_i - K_iC_j) & \overline{D}_i \\ 0 & 0 & -L_iC_j & 0 \end{bmatrix}$$

The main result is stated in the following theorem

Theorem: The fuzzy control system as given by (18) is stable if the controller and the observer gains are set to $G_j = M_{a11}^{-1}Y_j$ and $N_i = P_{a22}^{-1}O_i$ and $\overline{E}_i = P_2^{-1}X_i$ with the matrices X_i, M_{a11}, Y_j and O_i satisfying the following LMEs.

$$M_{a11}A_i^T + A_iM_{a11} - (B_iY_j)^T - (B_iY_j) = -\delta I \quad (19)$$

$$A_i^TP_{a22} + P_{a22}A_i - (O_iC_j)^T - (O_iC_j) = -\delta I \quad (20)$$

$$H_{bij}^TP_2 + P_2H_{bij} - (X_i\overline{C}_j)^T - (X_i\overline{C}_j) = -\delta I \quad (21)$$

Proof. The proof can be given directly from [17].

C. Calculation of Gains for the Fuzzy Observers and the Fuzzy Controller

If there exists a common positive definite matrix P such that

$$PH_{ij} + H_{ij}^TP < 0 \qquad \forall i, j \quad (22)$$

Then, the equilibrium of a fuzzy control system (18) is asymptotically stable at large using the control law (9), the matrices H_{ij}, ΔH_{ij}, S_i and P can be expressed as:

$$H_{ij} = \begin{bmatrix} H_{aij} & H_{cij} \\ 0_{2x2} & H_{bij} - \overline{E}_i\overline{C}_{ij} \end{bmatrix}, \Delta H_{ij} = \begin{bmatrix} \Delta\overline{A}_{ia} & 0_{2x2} \\ \Delta\overline{A}_{ib} & 0_{2x2} \end{bmatrix},$$

$$P = \begin{bmatrix} P_1 & 0_{2x2} \\ 0_{2x2} & P_2 \end{bmatrix} \mathrm{S_i} = \begin{bmatrix} \overline{B}_i \\ 0 \end{bmatrix}, \overline{\mathrm{B}}_\mathrm{i} = \begin{bmatrix} B_i \\ 0 \end{bmatrix},$$

$$\Delta\overline{A}_{ia} = \begin{bmatrix} \Delta A_i & 0 \\ (\Delta A_i - NFC_j) & 0 \end{bmatrix}, \Delta\overline{A}_{ib} = \begin{bmatrix} (\Delta A_i - K_iFC_j) & 0 \\ L_iFC_i & 0 \end{bmatrix},$$

$$H_{aij} = \begin{bmatrix} (A_i - B_iG_j) & B_iG_j \\ 0 & (A_i - N_iC_j) \end{bmatrix}$$

$$H_{bij} = \begin{bmatrix} A_i & \overline{D}_i \\ 0 & 0 \end{bmatrix}, H_{cij} = \begin{bmatrix} 0 & \overline{D}_j \\ 0 & \overline{D}_i \end{bmatrix}, \overline{E}_i = \begin{bmatrix} K_i \\ L_i \end{bmatrix}, \overline{C}_j = \begin{bmatrix} C \\ 0 \end{bmatrix}^T$$

Therefore, the inequality (22) will be rewritten as:

$$H_{aij}P_1 + P_1H_{aij}^T < 0 \qquad \forall i, j \quad (23)$$

$$(H_{bij} - \overline{E}_i\overline{C}_{ij})P_2 + P_2(H_{bij} - \overline{E}_i\overline{C}_{ij}) < 0 \qquad \forall i, j \quad (24)$$

Equations (23) and (24) are a set of Nonlinear Matrix Inequalities (NLMs) and for the convenience of design should be transformed into pure LMIs as follows: Assuming $P_1 = diag(P_{a11}, P_{a22})$, by multiplying (24) from the left and right by $M_{a11} = P_{a11}^{-1}$ and applying the change of variables $Y_j = G_j M_{a11}$ and $O_i = P_{a22}N_i$ and $X_i = P_2\overline{E}_i$, the following LMIs conditions are obtained:

$$M_{a11}A_i^T + A_iM_{a11} - (B_iY_j)^T - (B_iY_j) < 0 \quad (25)$$

$$A_i^TP_{a22} + P_{a22}A_i - (O_iC_j)^T - (O_iC_j) < 0 \quad (26)$$

$$H_{bij}^TP_2 + P_2H_{bij} - (X_i\overline{C}_j)^T - (X_i\overline{C}_j) < 0 \quad (27)$$

By transforming the inequalities (25)-(27) into equality, the above inequality will be rewritten and the LMEs (19)-(21) are obtained.

IV. WES MODEL AND SIMULATIONS

In this section, a WES example is presented to demonstrate the effectiveness of the proposed design method.

A. WES State-Space Modeling

State-Space of 660 kW wind turbine can be described by the following nonlinear equations from [18], [19].

$$\dot{x}(t) = g(x) + Bu(t), \quad y(t) = Cx(t) \quad (28)$$

where $g(x) = \begin{bmatrix} \frac{\overline{V}_s}{J\omega_s}I_{qr} - \frac{T_m}{J} - \frac{F_v}{J}(\omega_r - \omega_s) \\ \frac{-R_r}{L_r'}I_{qr} - \omega_rI_{dr} - \omega_r\frac{\overline{V}_s}{L_r'\omega_s} \\ \frac{-R_r}{L_r'}I_{dr} + \omega_rI_{qr} \end{bmatrix}$,

$$B = \begin{bmatrix} 0 & 0 \\ 0 & \frac{1}{L_r'} \\ \frac{1}{L_r'} & 0 \end{bmatrix}, C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -\overline{V}_s & 0 \end{bmatrix}, \overline{V}_s = \frac{MV_s}{L_s}$$

$$x=\begin{bmatrix}x_1\\x_2\\x_3\end{bmatrix}=\begin{bmatrix}\omega_r\\I_{qr}\\I_{dr}\end{bmatrix},\ y(t)=\begin{bmatrix}y_1\\y_2\end{bmatrix}=\begin{bmatrix}\omega_r\\P_s\end{bmatrix},u(t)=\begin{bmatrix}u_1\\u_2\end{bmatrix}=\begin{bmatrix}V_{dr}\\V_{qr}\end{bmatrix},$$

I_{dr} and I_{qr} denote the direct and quadrature rotor currents respectively, V_{dr} and V_{qr} are the direct and quadrature rotor voltages respectively, M is the magnetizing inductance, L_s and L'_r are the stator and rotor windings inductances respectively, V_s is the stator voltage magnitude, R_r is the rotor windings resistance, J is the rotor inertia, T_m and T_e are the rotor mechanical and electromagnetic torques respectively, F_v is the viscous torque coefficient, and P_s is the stator active power.

The mechanical power, P_{mech}, can be determined by [20],

$$P_{mech}=0.5C_p(\lambda,\ \beta_p)\,\rho\pi R^2V^3 \tag{29}$$

$$\lambda=\ \Omega R/V \tag{30}$$

where C_p is the power coefficient, β_p is the pitch angle, λ is the tip speed ratio, V is the wind speed, Ω is the turbine rotational speed ($\Omega=\ \omega/n$), n is the gear box ratio, ω is the rotor angular speed and is given by $\omega=\omega_s-\omega_r$, where ω_s, ω_r are the stator and rotor electrical frequencies respectively, R is the rotor-plane radius, and ρ is the air density. It can be stated that, for a specified wind velocity, there is a turbine rotational speed value that allows the capturing of the maximum mechanical power attainable from the wind.

B. *TS Fuzzy WES Description*

The WES can be represented by a TS-fuzzy plant model having two rules with ω_r as the premise variable The *ith* rule can be written as follows, $i=1,2$.

Rule i: IF x_1 is M_i

Then $\dot{x}(t)=(A_i+\Delta A_i)x(t)+B_iu(t)+(B_d+\Delta B_d)+\overline{D}_i d(t)$ (31)

The system dynamics are described by

$$\dot{x}(t)=\sum_{i=1}^{2}\mu_i[(A_i+\Delta A_i)x(t)+B_iu(t)+(B_d+\Delta B_d)+\overline{D}_i d(t)] \tag{32}$$

where $x(t)\epsilon\kappa^{3x1}$ and $u(t)\epsilon\kappa^{2x1}$ are the state vectors and the control input, respectively. In the case of parametric uncertainty, the dynamic equations of the model are known but some parameters (J and R_r) are uncertain. This kind of uncertainty is common in models obtained by linearization. Any uncertain parameter p_u is assumed to fall within a range $[p_{umin},\ p_{umax}]$ and is generally normalized in the form $p_{ui}=p_{ui,o}+\Delta p_u$, where $p_{ui,o}$ is the nominal value, Δp_u is uncertain value confined to the bounded range. If ΔJ and ΔR_r are denoted as the uncertainties introduced by system parameters J and R_r, respectively, then from (32), the uncertain matrices can be expressed as

$$A_1+\Delta A_1=\begin{bmatrix}-\dfrac{F_v}{J+\Delta J} & \dfrac{\overline{V}_s}{(J+\Delta J)\omega_s} & 0\\ -\dfrac{\overline{V}_s}{L'_r\omega_s} & \dfrac{-R_r+\Delta R_r}{L'_r} & -\ f_{1\max}\\ 0 & f_{1\max} & \dfrac{-R_r+\Delta R_r}{L'_r}\end{bmatrix},$$

$$A_2+\Delta A_2=\begin{bmatrix}-\dfrac{F_v}{J+\Delta J} & \dfrac{\overline{V}_s}{(J+\Delta J)\omega_s} & 0\\ -\dfrac{\overline{V}_s}{L'_r\omega_s} & \dfrac{-R_r+\Delta R_r}{L'_r} & -\ f_{1\min}\\ 0 & f_{1\min} & \dfrac{-R_r+\Delta R_r}{L'_r}\end{bmatrix},$$

$$B_i=\begin{bmatrix}0 & 0\\ 0 & \dfrac{1}{L'_r}\\ \dfrac{1}{L'_r} & 0\end{bmatrix},d=\begin{bmatrix}d_1\\d_2\end{bmatrix},\overline{D}_i=\begin{bmatrix}0 & 0\\0 & -1\\1 & 0\end{bmatrix},B_d=\begin{bmatrix}\dfrac{-1}{J+\Delta J}(T_m-\omega_s)\\0\\0\end{bmatrix}$$

where $M_i(x_1)$ are the membership functions as shown in Fig. 1 and are given by:

$$M_1(x_1)=\frac{f(x_1)-f_{\min}}{f_{\max}-f_{\min}},\ M_2(x_1)=1-M_1(x_1) \tag{33}$$

A two-rule fuzzy controller is designed for the nonlinear plant. The rules are listed as follows.

Rule j: IF x_1 is M_j

Then $u(t)=-G_jx(t)-D_j\hat{d}(t)+r(t)$, j=1,2 (34)

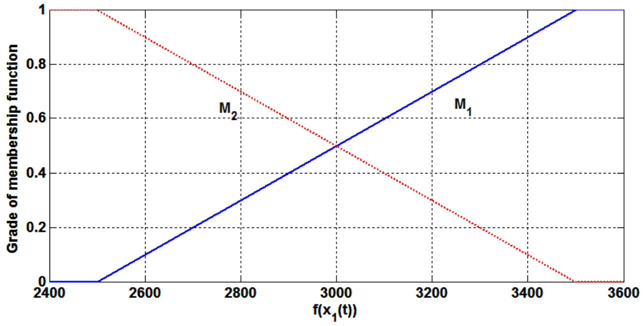

Fig. 1. Membership functions of state x_1

By solving the LMEs (19)-(21) related to the wind turbine system we can see that the uncertainty is affected by δ as shown in the Fig.2, since at certain value of δ the control system is stable in present large value of uncertainty.

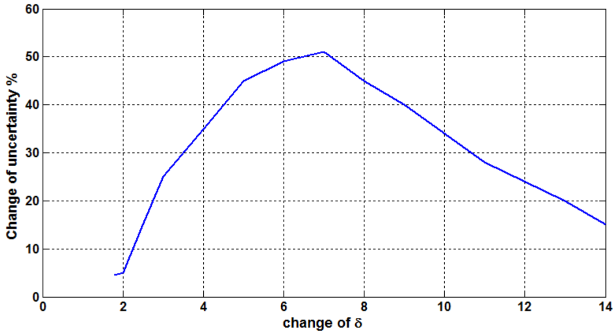

Fig.2. change of uncertainty with δ

C. Simulation and Results

The proposed controller for the WES is tested for random variation of wind speed as shown in Fig.3. The control objective of this paper is to design a FTC law for system (28) to ensure that all signals in the closed-loop system are bounded and the output ω tracks as closely as possible the given reference signal $r(t)=\omega_{ref}=\omega_{opt}=\lambda_{opt}V/R$ profile, where $r(t)$ is chosen in such a way as to follow the optimal tip speed ratio (λ_{opt}) though there are unknown inputs d_1 and d_2 as shown in Fig. 4, where (d_1 and d_2 are the unknown input signals on rotational speed of the turbine and generator, respectively), sensor faults, for the control purpose, it is required that at one sensor fail every time, we modelled the faults as proportional signals to sensor outputs as shown in Fig. 5 and the parameters uncertainties J and R_r are changed within 35% of their nominal values.

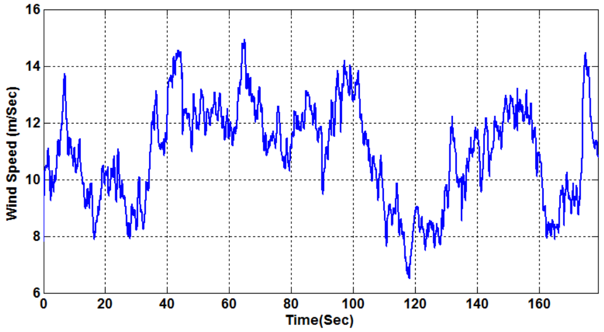

Fig. 3. Wind speed profile

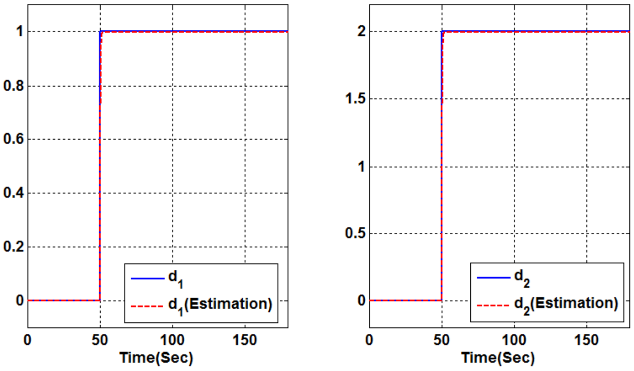

Fig. 4. unknown input d_1 and its estimate (left) and unknown input d_2 and its estimate (right)

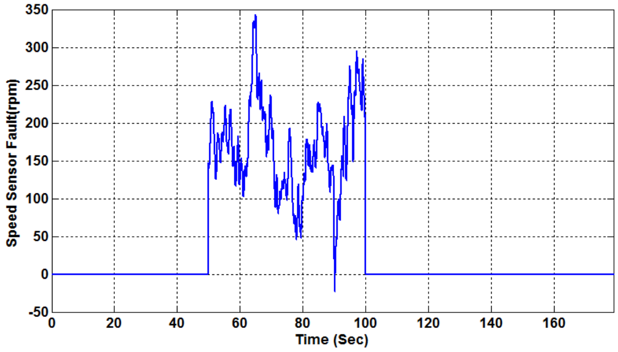

Fig. 5. Proportional error on the generator speed sensor

Fig. 6 and Fig. 7 show the rotor angular speed (solid line) and its estimate (dotted line) and the active power P_s (solid line) and its estimate (dotted line), respectively, without FTC scheme strategy (left) and with FTC scheme strategy (right). From simulation results of applying the proposed control scheme to the system (28) for tracking the reference signal (dashed line), we can see that the outputs of the system are bounded and good tracking performance can be obtained though the nonlinearities of the system, sensor faults and all unknown inputs.

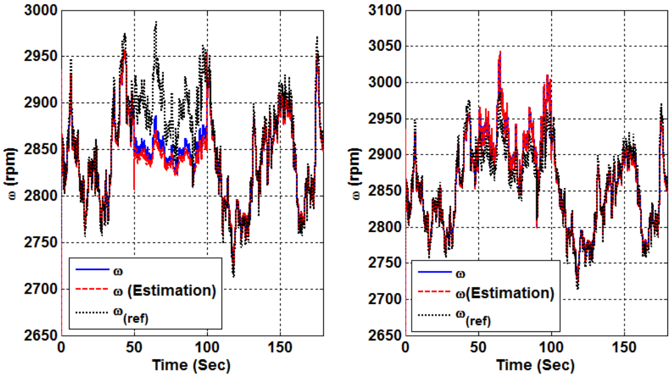

Fig. 6. The trajectories of ω and its estimate without (left) and with (right) FTC strategy

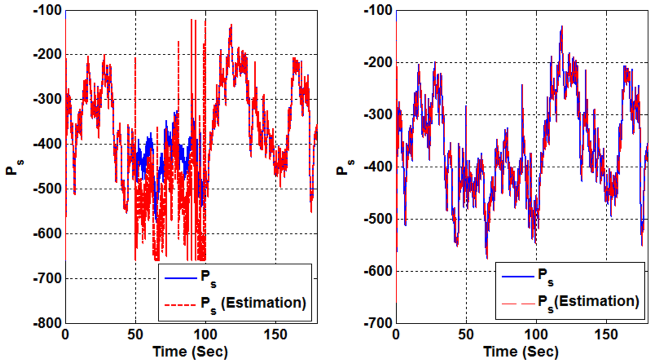

Fig. 7. The trajectories of P_s and its estimate without (left) and with (right) FTC strategy

From the simulation, it has been presented that the proposed scheme is able to detect and isolate sensor faults, which are the faults in the generator speed, by a proper and feasible selection of the healthy observed variables and compensate the unknown inputs by the nonlinear unknown inputs observers. The simulation results demonstrate the effectiveness of the proposed control approach. The proposed control scheme can guarantee the stability of the closed-loop system and the convergence of the output tracking error.

V. CONCLUSION

In this paper, based on the TS fuzzy model, we have studied the robust fuzzy observer-based FTC problem for continuous-time nonlinear systems with parametric uncertainties, sensor faults and unknown-inputs. The sufficient condition for the existence of a robust fuzzy observer-based controller is presented in the form of a set of LMIs and LMEs. The FTC gains and observer gains matrices can be obtained by directly solving this set of LME. Moreover, we have presented a method of detecting and isolating a single sensor fault occurring in a particular class of continuous-time uncertain nonlinear systems with unknown-inputs and sensor faults. LME and LMI conditions are given for checking the feasibility of designing the unknown-input observer and fuzzy FTC controller used in this scheme. Finally, simulation results indicate that the proposed method is effective. One of the future research topics is to extend the result developed in this paper to the robust fuzzy observer-based control design for discrete-time uncertain TS fuzzy systems with parametric uncertainties, sensor faults and unknown-inputs

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