Robust LMI-based active fault tolerant pitch control of a wind turbine using fuzzy model

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Abstract: This article investigates a robust active fault tolerant control strategy for a wind turbine system involving disturbance, actuator and sensor fault. The state-space representation of the system is formulated by the Takagi-Sugeno fuzzy model, and a disturbance rejection technique is used to eliminate the wind perturbation. To guarantee the robust behavior of the system, the control signal is reconfigured via addition of a robust term. Using the Lyapunov method, some criteria, expressed in the form of linear matrix inequalities (LMIs), are provided for asymptotic stability of the estimated error. The mail results are confirmed by numerical simulations of a 1 MW wind turbine.

Keywords: Fault tolerant control; LMI; Pitch control; Takagi-Sugeno model; Robust behavior; Wind turbine

1. INTRODUCTION

The traditional fossil and nuclear energy threaten the natural environment. One of the well-known renewable energy is the wind energy in order to reduce the fossil and nuclear fuels consumption. A wind turbine, as a controversial issue, absorbs the wind energy. Considering the probability of fault occurrence in industrial systems, maintaining the system performance is essential under distinct faults to reduce the electrical energy production cost. The combination of fault diagnosis and identification (FDI) with the control reconfiguration (CR) is called fault tolerant control (FTC). Different types of faults, such as pitch and hydraulic system faults (Odgaard and Johnson, 2013), may be occurred in the wind turbines. In fact, the occurrence of such faults in a wind turbine under the full load area can significantly jeopardize the system's performance and even lead to a poor stability of the pitch control system. Several techniques of FDI and FTC schemes for horizontal wind turbine were reviewed in (Saha and Singh, 2019). However, a turbine has different dynamics and the control inputs, including the generator torque and the pitch angle, should be designed to achieve the system requirements separately. Different regions are determined subject to the values of rotor speed and generator torque. In the pitch control region, the rotor speed is greater than the set-point value and the generator torque has its maximum value. The pitch control and the torque control are two separate control strategies used in the wind turbine because of the dynamic variations of the system nature (Burton et al., 2011). Nourdine et al., 2010 introduced a pitch control for each blade with linear quadratic Gaussian controller and load reduction was introduced. In (Taher et al., 2013), an optimization problem was studied for designing a bank of linear quadratic regulator (LQR) controllers in a gain scheduling strategy. Habibi et al., 2019 studied a model based on FDI and FTC techniques in wind turbine was presented. Odgaard et al., 2013 proposed a benchmark model for accommodation and fault detection. The model configuration consists of three-bladed pitch-controlled variable-speed. Solving bi-linear matrix inequalities (Sloth et al., 2011), both passive and active FTC strategies in the full load region have been investigated for the pitch system. In (Blesa et al., 2014), the FDI and the FTC have been applied on a wind turbine in order identify sensor and actuator faults using interval observers and virtual sensors/actuators, respectively. In addition, the batch least squares technique was used for the faults estimation. In (Azizi et al., 2019), an adaptive output-feedback sliding mode technique was employed to construct a FTC of wind turbine. In (Ettouil et al., 2018), a synergetic FTC control for pitch system has been developed by means of an adaptive observer. Using automatic signal correction, an active FTC scheme based on fault detection and diagnosis (FDD) was proposed to control wind turbine pitch angle in presence of uncertainties and measurement noise (Badihi et al., 2020).

In practice, since the exact value of effective wind speed is not available, the wind speed was estimated using the Kalman filter. In addition, a nonlinear state-feedback controller was designed to achieve desired performance. Soltani et al., 2013 reprted a comprehensive study of distinct techniques for wind speed estimation. In (Shi and Patton, 2015), the system states and the fault signals were estimated by an extended state observer in a linear parameter varying system, while the pole-placement and H∞ optimization ensure the performance requirements and the overall closed-loop robustness. In (Casau et al., 2015), a set-valued observer was used for fault detection of an uncertain linear time-varying system against exogenous disturbances, measurement noise and model uncertainty. Both active and passive FTC have been applied for the purpose of the system configuration. In (Simani and Castaldi, 2014), a nonlinear geometric approach based adaptive filters was introduced for fault estimation and stability of the system was analysed under different faults. A time varying estimator using active FTC strategy was designed to eliminate sensor fault effect in (Li et al., 2020). Stability analysis of estimator and model predictive controller was investigated using LMI technique. A robust sliding mode observer design for sensor faults along with online linearization was presented in (Ghanbarpour et al., 2020). Xiahou et al., 2020 considered the stator and rotor current sensor faults occurred in a doubly-fed induction generator. Sensor faults were tolerated by reconfiguration structure considering vector control scheme.

Fuzzy-based fault tolerant controller is another technique, which has received great attentions, recently. In (Badihi et al., 2014), a fuzzy gain scheduling algorithm with a proportional-integral controller was designed under measurement noise, wind turbulence as well as different faults. Georg and Schulte, 2014 implemented a sector non-linearity approach together Takagi-Sugeno Sliding Mode Observer (TS SMO) on a non-affine complex wind turbine system. Besides, the existence of sliding motion has been proved through the reachability condition. In (Schulte and Gauterin, 2015), the fault reconstruction strategy was exploited to correct inputs as virtual actuators in a hydrostatic wind turbine, and TS SMO scheme was applied to achieve the FDI and the FTC. Motivated by above discussions, here, we investigate a robust active FTC (RFTC) for pitch control under the full load operation against disturbance and actuator faults. The contributions of the current research are listed below:

1) A novel RFTC is developed based on a nonlinear model of wind turbine. Simplicity of design, robust behaviour against faults and disturbance, as well as fast response are the prominent properties of the introduced control technique. Notice that the proposed RFTC based on modelling of the turbine has been rarely studied in the literature.

2) A set of TS fuzzy models are adopted to estimate the system nonlinearities, and sufficient conditions are provided to stabilize the system using the linear matrix inequalities (LMIs). The proposed control strategy based on the model for the wind turbine used in this paper has been rarely reported in the literature, as well.

3) An extended observer is designed for states and faults estimations simultaneously. Furthermore, the stability of the entire system including observer and FTC controller is analysed using the Lyapunov method.

It should be noted that the key novelty of this article consists of the closed loop stability analysis of nonlinear system in a region of convergence under disturbance, sensor and actuator faults.

In the follow-up, the problem description is given in Section 2. Fault tolerant scheme with disturbance rejection problem is explained in Section 3. The proposed control performance is assessed using numerical simulations in Section 4 which is consists of actuator faults, sensor faults and comparison scenario. Eventually, conclusion is outlined in Section 5.

2. PROBLEM FORMULATION

This paper concerns with the problem of pitch control under the full load operation for a wind turbine. The nonlinear dynamical equations of the system under study is given by (Kühne et al., 2018).

$$\begin{cases} \dot{\theta}_s(t) = \omega_r(t) - \omega_g(t) \\ \dot{\omega}_r(t) = -\dfrac{\overline{K}_s}{J_r}\theta_s - \dfrac{\overline{B}_s}{J_r}\omega_r + \dfrac{\overline{B}_s}{J_r}\omega_g + \dfrac{\overline{T}_r}{J_r} \\ \dot{\omega}_g(t) = \dfrac{\overline{K}_s}{J_g}\theta_s - \dfrac{\overline{B}_s}{J_g}\omega_r - \dfrac{\overline{B}_s}{J_r}\omega_g - \dfrac{\overline{T}_g}{J_g} \\ \dot{\beta}(t) = -\dfrac{1}{\tau}\beta + \dfrac{1}{\tau}\beta_d \end{cases} \tag{1}$$

where θ_s, ω_r, ω_g and β are shaft torsion angle, rotor angular velocity, generator angular velocity and pitch angle respectively. Table 1 list the other parameters of wind turbine.

The aerodynamic torque is determined by

$$\overline{T}_r = \frac{1}{2\lambda}\rho\pi R^3 C_P(\lambda,\beta)\upsilon^2 \tag{2}$$

where C_P (λ, β), λ and v are the power coefficient, the blade tip speed ratio and wind speed respectively, defined by

$$\lambda = \frac{R\omega_r}{\upsilon} \tag{3}$$

T_r can be linearized as

$$\overline{T}_r = T_{r\upsilon}\upsilon + T_{r\beta}\beta \tag{4}$$

Where

$$\begin{aligned} T_{r\nu} &= \frac{d\overline{T}_r}{d\upsilon}\Big|(\upsilon*,\beta*) \\ T_{r\beta} &= \frac{d\overline{T}_r}{d\beta}\Big|(\upsilon*,\beta*) \end{aligned} \tag{5}$$

It should be noted that the C_P (λ, β) is computed by using a look-up table. There are several mathematical estimations to approximate the coefficient (for example refer to (Kamal et al., 2012)). We consider the generator torque $\overline{T}_g$ as a function of generator speed whereas its reference is given by

$$\overline{T}_g = \overline{B}_g\omega_g - T_{g,ref} \tag{6}$$

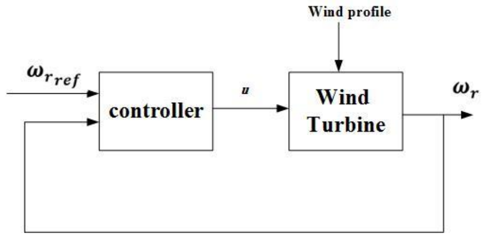

Fig. 1. Base-line control structure for wind turbine.

In this section, a set of locally linear models are constructed based on a TS fuzzy model for estimating the original nonlinear dynamical system given by (Tanaka and Wang, 2003). The state-space realization of ith rules is denoted as

Rule i

IF

$$\gamma_1(x,u)\ \ is\ \ \psi_{i1}\ \ \ and...and\ \ \gamma_p(x,u)\ \ is\ \ \psi_{ip} \tag{7}$$

Then

$$\begin{cases} \dot{x}(t) = A_i x(t) + Bu(t) + B_{\upsilon_i}\upsilon(t) + B_f f_1(t) \\ y(t) = Cx(t) + D_f f_2(t) \qquad\qquad i = 1,2,...,n \end{cases}$$

where the states are represented as

$$x = (\theta_s, \omega_r, \omega_g, \beta)^T \tag{8}$$

The state-space representation is expressed as

$$A = \begin{bmatrix} 0 & 1 & -1 & 0 \\ -\dfrac{\bar{K}_s}{\bar{J}_r} & -\dfrac{\bar{B}_s}{\bar{J}_r} & \dfrac{\bar{B}_s}{\bar{J}_r} & -\dfrac{\bar{T}_{rB}}{\bar{J}_r} \\ \dfrac{\bar{K}_s}{\bar{J}_g} & \dfrac{\bar{B}_s}{\bar{J}_g} & -\dfrac{\bar{B}_s + \bar{B}_g}{\bar{J}_g} & 0 \\ 0 & 0 & 0 & -\dfrac{1}{\tau} \end{bmatrix},\ B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & \dfrac{1}{\bar{J}_g} \\ \dfrac{1}{\tau} & 0 \end{bmatrix}$$
$$B_\upsilon = \begin{bmatrix} 0 \\ \dfrac{T_{r\upsilon}}{\bar{J}_r} \\ 0 \\ 0 \end{bmatrix},\ C^T = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} \tag{9}$$

Fig. 1 shows the base-line control strategy. Considering fault, we add an estimator block to the control configuration. The structure of FTC system is given by Fig. 2.

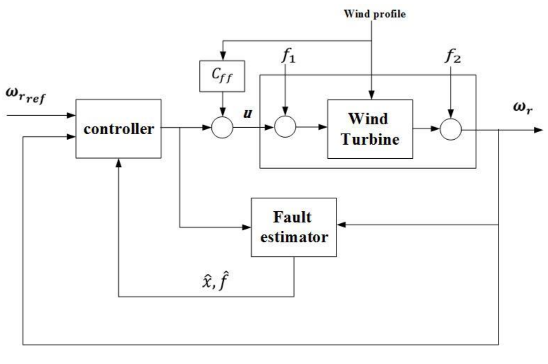

Fig. 2. FTC diagram for wind turbine.

3. FAULT TOLERANT CONTROLLER DESIGN WITH DISTURBANCE REJECTION

There are different techniques in the FTC due to the system requirements. In this paper, fault estimation is augmented with base-line controller for designing a FTC scheme. Accordingly, to estimate the system states and the fault effects, an unknown input observer is designed. The FTC rule can be achieved by a compensating term as

$$u = \sum_{i=1}^{n} \gamma_i(z(x,u)) \left(u_{base_i} + u_{cr_i} + u_{FTC}\right) \tag{12}$$

where u_{FTC} and u_{cr} are the fault compensation and the disturbance rejection parts, respectively.

3.1. Disturbance Rejection Strategy

First, disturbance rejection is followed by the feed-forward strategy. Accordingly, the compensating feed-forward term C_{ffi} is selected to eliminate the effect of disturbance in the system output. Let us consider the following disturbance compensation term.

$$u_{cr_i} = C_{ffi}\upsilon = [C_{ff1_i}, C_{ff2_i}]^T \upsilon \tag{13}$$

To compensate the effect of disturbance on the output, C_{ffi} is designed to satisfy (14).

$$u_{cr_i} = C_{ffi}\upsilon + G_{\upsilon i}\upsilon = 0 \tag{14}$$

where $G_{pi} = [G_{p1_i}, G_{p2_i}]$ and $G_{\upsilon i}$ are the plant and the disturbance transfer functions, respectively.

A possible solution for (14) is

$$C_{ff1_i} = -G_{p1_i}^{-1} G_{\upsilon i}\ \ and\ \ C_{ff2_i} = 0$$

Remark 1: Since C_{ff1_i} is not a proper transfer function, we can select an adequate filter to combat this problem.

3.2. Actuator Fault Tolerant Controller Design

In practice, a common choice for base-line controller is designed by LQR as $u_{base_i} = -K_i\hat{x} + N_i\omega_{r_{ref}}$. The constant coefficient N is used to eliminate the tracking error. Since the system's states are not available, we can formulate an observer to estimate the fault effects and the states of system. To attenuate the fault effects, a correction term is added as $u_{FTC} = E_f \hat{f}$. Due to consideration of actuator fault, hence D_f =0. The observer equations are

$$\begin{cases} \dot{\hat{x}} = (A_i - BK)\hat{x} + L(y - C\hat{x}) + BN_i\omega_{r_{ref}} \\ \dot{\hat{f}} = Q_i(y - C\hat{x}) \end{cases} \tag{15}$$

Defining $e = x - \hat{x}$ as the estimation error and after some mathematical manipulations, we obtain

$$\begin{bmatrix} \dot{e} \\ \dot{\hat{f}} \end{bmatrix} = \left(\begin{bmatrix} A_i & BE_f \\ 0 & 0 \end{bmatrix} - \begin{bmatrix} L_i \\ -Q_i \end{bmatrix} \begin{bmatrix} C & 0 \end{bmatrix} \right) \begin{bmatrix} e \\ \hat{f} \end{bmatrix} + \begin{bmatrix} B_f \\ 0 \end{bmatrix} f \tag{16}$$

Defining

$$\bar{E}=\begin{bmatrix}e^T & \hat{f}^T\end{bmatrix}^T,\ \bar{A}_i=\begin{bmatrix}A_i & BE_f\\ 0 & 0\end{bmatrix},\ \bar{B}=\begin{bmatrix}B_f\\ 0\end{bmatrix},$$

$$\bar{C}=\begin{bmatrix}C & 0\end{bmatrix}\ and\ \bar{L}_i=\begin{bmatrix}L_i\\ -Q_i\end{bmatrix}$$

(16) can be simplified as

$$\dot{\bar{E}}=(\bar{A}_i-\bar{L}_i\bar{C})\bar{E}+\bar{B}f \tag{17}$$

Where E_f should be designed to eliminate the effect of faulty steady-state. It is assumed that E_f exists such that $BE_f + B_f = 0$. Next, we analyze the stability of the entire system.

Theorem 1: Let the state-space realization of the turbine be described by (9). The controller gain K is designed in such a way that $A_i - BK_i$ ($i = 1, ..., n$) is Hurwitz, and the gain of observer $\bar{L}_i$ satisfies the following LMIs for a positive scalar Γ:

$$\begin{bmatrix}O_1 & 0 & 0 & \dots & 0\\ 0 & O_2 & 0 & \dots & 0\\ . & & & & \\ . & & & & \\ . & & & & \\ 0 & 0 & 0 & \dots & O_n\end{bmatrix}<0 \tag{18}$$

where

$$O_i=\begin{bmatrix}-2\Gamma^2 I & \bar{B}^T\\ B & \bar{A}_i-\bar{L}_i\bar{C}+\frac{1}{2}I\end{bmatrix}\qquad i=1,2,...,n \tag{19}$$

Then, the error $\bar{e}$ is finite gain L_2 stable.

Proof: we construct the following Lyapunov function.

$$V=\frac{1}{2}\bar{E}^T\bar{E} \tag{20}$$

where

$$\dot{\bar{E}}=\sum_{i=1}^{n}\gamma_i(z(x,u))\left((\bar{A}_i-\bar{L}_i\bar{C})\bar{E}+\bar{B}f\right)$$

The time derivative of (20) Lyapunov function is derived as

$$\begin{aligned}\dot{V}&=\sum_{i=1}^{n}\gamma_i(z(x,u))\left(\frac{\partial V}{\partial\bar{E}}(\bar{A}_i-\bar{L}_i\bar{C})\bar{e}+\frac{\partial V}{\partial\bar{E}}\bar{B}_f\right)\\ &=\sum_{i=1}^{n}\gamma_i(z(x,u))\begin{pmatrix}-\frac{1}{2}\Gamma^2\|f-\frac{1}{\Gamma^2}\bar{B}^T(\frac{\partial V}{\partial\bar{E}})^T\|_2^2\\ +\frac{\partial V}{\partial\bar{E}}(\bar{A}_i-\bar{L}_i\bar{C})\bar{e}\\ +\frac{1}{2\Gamma^2}\frac{\partial V}{\partial\bar{E}}\bar{B}\bar{B}^T(\frac{\partial V}{\partial\bar{E}})^T\end{pmatrix}\end{aligned} \tag{21}$$

From Eqs. (18) and (19) and using Schur complement lemma, we get

$$\bar{A}_i-\bar{L}_i\bar{C}+\frac{1}{2\Gamma^2}\bar{B}\bar{B}^T+\frac{1}{2}I\le 0,\qquad i=1,2,....,n \tag{22}$$

Using Eqs. (21) and (22), we have

$$\dot{V}\le\sum_{i=1}^{n}\gamma_i(z(x,u))\begin{pmatrix}\frac{1}{2}\Gamma^2\|u\|_2^2-\frac{1}{2}\|y\|_2^2\\ -\frac{1}{2}\Gamma^2\|u-\frac{1}{\Gamma^2}\bar{B}^T(\frac{\partial V}{\partial\bar{E}})^T\|_2^2\end{pmatrix} \tag{23}$$

From there, we have

$$\dot{V}\le\sum_{i=1}^{n}\gamma_i(z(x,u))\left(\frac{1}{2}\Gamma^2\|u\|_2^2-\frac{1}{2}\|y\|_2^2\right) \tag{24}$$

Integrating Eq. (24) concludes

$$V(x(t))-V(x(0))\le n\begin{pmatrix}\frac{1}{2}\Gamma^2\int_0^t\|u(\tau)\|_2^2\,d\tau\\ -\frac{1}{2}\int_0^t\|y(\tau)\|_2^2\,d\tau\end{pmatrix} \tag{25}$$

Finally, by mathematical manipulations, it is straightforward to see that the finite gain L_2 stability of error is proved as follows.

$$\|y\|_{L2}\le\Gamma\|u\|_{L2}+\sqrt{\frac{2V(x_0)}{n}} \tag{26}$$

3.3. Sensor Fault Tolerant Controller Design

Based line controller design and disturbance rejection structure are as the same as before. To design an FTC controller, we need to estimate the fault. To achieve this goal, the sensor fault is estimated by the proposed observer. Due to consideration of sensor fault, hence $B_f = 0$. The control structure is the same as before and depicted in Fig. 2. All of the true state values are estimated by the proposed observer without being influenced by occurred faults in the system. Therefore, the base line controller without being affected by fault can work properly. Eq. 12 shows the fuzzy control rule for disturbance rejection, FTC and base line controller. Equivalent state space representation is as follow:

$$\begin{cases}M\,\dot{Z}(t)=A_{s_i}\,Z(t)+Bu(t)\\ y(t)=C_s\,Z(t)\end{cases} \tag{27}$$

where the state vector $ZT = [x^T\ f^T]$ and the matrices M, A_{si}, C_s are defined as:

$$M=[I,0],\qquad A_{s_i}=[A_{s_i},0],\qquad C_s=[C,D_f] \tag{28}$$

By defining matrix W as

$$W=\begin{bmatrix}M\\ C_s\end{bmatrix}=\begin{bmatrix}I & 0\\ C & D_f\end{bmatrix} \tag{29}$$

Assumption: We assume that the matrix D_f is a full column rank. Consequently, there exists left inverse of matrix W such that

$$[U\ V]\,W=I \tag{30}$$

where matrix $[U \;\; V]$ denotes the left inverse of W. The observer equations are

$$\begin{cases} \dot{\xi}(t) = (UA_{s_i} - L_i C_{s_i})\xi(t) \\ +(L + UA_{s_i} V - L_i C_{s_i} V) y(t) + B u(t) \\ \hat{Z}(t) = \xi(t) + V\, y(t) \end{cases} \tag{31}$$

It can be shown that sensor fault $f_2(t)$ can be estimated by:

$$D_f \; \hat{f}_2(t) = y(t) - C\,M\,Z(t) \tag{32}$$

u_{FTC} should be designed such that the sensor fault effect on the output is tolerated. It can be seen that $u_{FTC}(t) = -N((y(t) - CMZ(t))$ removes the fault effect.

Theorem 2 For given the state-space realization of the turbine described by Eq. (9), the controller gain K is designed in such a way that $A_i - BK_i$ is Hurwitz for $i = 1, ..., n$. It is assumed that (UA_{si}, C_{si}) is observable and the observer gain L_i satisfies the following inequality for a symmetric positive definite matrix P:

$$(UA_{s_i} - L_i C_{s_i})^T P + P(UA_{s_i} - L_i C_{s_i}) < 0 \tag{33}$$

Proof By defining $e(t) = z(t) - \hat{z}(t)$ and constructing the Lyapunov function $V(t)=e^T(t)Pe(t)$, we have

$$\dot{e} = \dot{Z}(t) - \dot{\hat{Z}}(t) = \dot{Z}(t) - \dot{\xi}(t) + V\,\dot{y}(t) \tag{34}$$

$$= (I - V\,C_s)\,\dot{Z}(t) - \dot{\xi}(t) \tag{35}$$

By substituting $Z^{\cdot}$ and $\xi^{\cdot}$ in Eq. (34)

$$\begin{aligned} \dot{e} &= U(A_{s_i} Z(t) + B u(t)) - ((UA_{s_i} - L_i C_{s_i})\xi(t) \\ &+ (L_i + UA_{s_i} V - L_i C_{s_i} V) y(t) + UBu(t)) \end{aligned} \tag{36}$$

After some manipulations we have:

$$\dot{e}(t) = (UA_{s_i} - L_i C_{s_i}) e(t) \tag{37}$$

Also time derivative of the Lyapunov function is calculated as:

$$\begin{aligned} &V(t) = \dot{e}^T(t)\,P\,e(t) + e^T(t) P\,\dot{e}(t) = \\ &e^T(t)((UA_{s_i} - L_i C_{s_i})^T P + P(UA_{s_i} - L_i C_{s_i}))e(t) \end{aligned} \tag{38}$$

The stability proof can be verified by:

$$(UA_{s_i} - L_i C_{s_i})^T P + P(UA_{s_i} - L_i C_{s_i}) < 0 \tag{39}$$

4. SIMULATION RESULTS

Here, we illustrate and assess the capability of the proposed FTC by simulations. Results are given in Figs. 3-13. Table. 1 tabulate the parameters of 1MW wind turbine used in the simulation. The proposed FTC-based controller is evaluated for random variation of wind profile around the speed of 12 units, as shown in Fig. 3. The control goal is to achieve the rotor speed to the $5\,{}^{rad}\!/_{s}$ value while no fault occurs or in the FTC design. Based on the previous description, the wind speed plays a prominent role in the control design.

Table 1. Numerical value of a 1 MW wind turbine

Turbine parameters	Description	Values	Dimension
K_s	Drivetrain stiffness parameter	1.566×10^6	N/m
$\bar{B}_s$	Drivetrain damping constant	3029.5	Nms/rad
$\bar{J}_r$	Rotor inertia	83×10^4	kg m^2
$\bar{J}_g$	Generator inertia	5.9	kg m^2
τ	Delay time constant for pitch dynamics	500×10^{-6}	s
ρ	Air density	1.225	kg m^3
R	Rotor radius	30.3	m

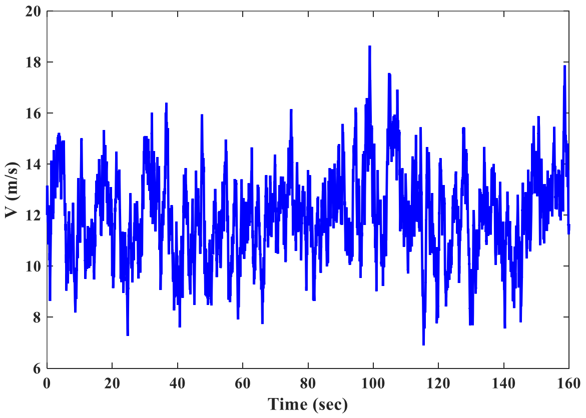

Fig. 3. The Wind speed

The TS model should emulate the wind turbine dynamics. Therefore, (1) can be expressed by a set of TS fuzzy models as:

$$A_1 = \begin{bmatrix} 0 & 1 & -1 & 0 \\ -\dfrac{\bar{K}_s}{\bar{J}_r} & -\dfrac{\bar{B}_s}{\bar{J}_r} & \dfrac{\bar{B}_s}{\bar{J}_r} & \dfrac{f_{1\min}}{\bar{J}_r} \\ \dfrac{\bar{K}_s}{\bar{J}_g} & \dfrac{\bar{B}_s}{\bar{J}_g} & -\dfrac{(\bar{B}_s + \bar{B}_g)}{\bar{J}_g} & 0 \\ 0 & 0 & 0 & -\dfrac{1}{\tau} \end{bmatrix}, \quad W_1 = \begin{bmatrix} 0 \\ \dfrac{f_{2\min}}{J_r} \\ 0 \\ 0 \end{bmatrix}$$

$$A_2 = A_1, \qquad W_2 = \begin{bmatrix} 0 \\ \dfrac{f_{2_{\max}}}{J_r} \\ 0 \\ 0 \end{bmatrix}$$

$$A_3 = \begin{bmatrix} 0 & 1 & -1 & 0 \\ -\dfrac{\bar{K}_s}{\bar{J}_r} & -\dfrac{\bar{B}_s}{\bar{J}_r} & \dfrac{\bar{B}_s}{\bar{J}_r} & \dfrac{f_{1_{\max}}}{\bar{J}_r} \\ \dfrac{\bar{K}_s}{\bar{J}_g} & \dfrac{\bar{B}_s}{\bar{J}_g} & -\dfrac{(\bar{B}_s + \bar{B}_g)}{\bar{J}_g} & 0 \\ 0 & 0 & 0 & \dfrac{1}{\tau} \end{bmatrix}, \quad W_3 = W_1$$

$$A_4 = A_3, \; W_4 = W_2 \qquad (40)$$

$$B_i = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & \dfrac{1}{\bar{J}_g} \\ \dfrac{1}{\tau} & 0 \end{bmatrix}, \qquad i = 1, \ldots, 4$$

We can easily obtain $f_{i\min}$ and $f_{i\max}$, i = 1, 2 in (Kamal et al., 2012). In the following, the actuator and sensor faults are estimated as the faults occur.

4.1. Actuator fault

The actuator fault is considered as a periodic signal. The gains of base-line controller and observer are designed as:

$$K = \begin{bmatrix} -0.0336 & -0.4472 & 0.001 & 0.0489 \\ 0.001 & -0.002 & 0.002 & 0.001 \end{bmatrix} \qquad (41)$$

$$L = \begin{bmatrix} 0.001 & 1.3497 & 1.3479 & -1 \end{bmatrix}$$

As shown in Fig. 4, the performance of estimation actuator fault has a good precision. Fig. 5 illustrates the estimated states $\hat{\theta}(s), \hat{\omega}_r, \hat{\omega}_g, \hat{\beta}$. Fig. 6 shows the system output and its reference. The control signals are depicted in Fig. 7 which are acceptable in practice.

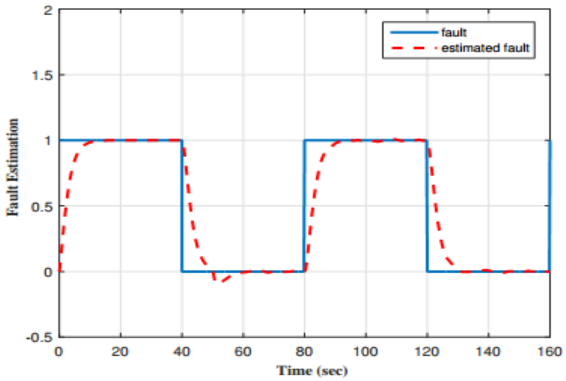

Fig. 4. Actual and estimated fault (actuator)

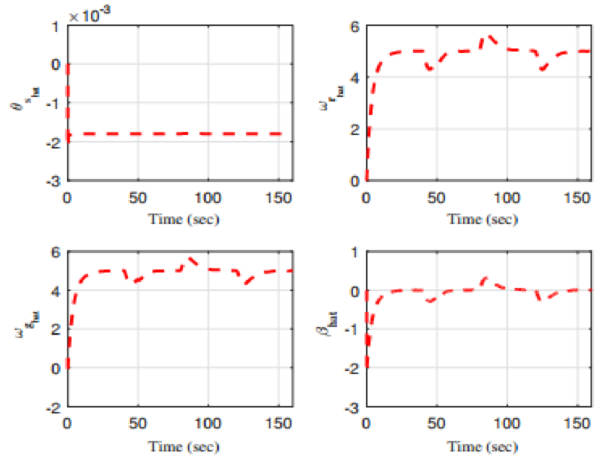

Fig. 5. Estimated states

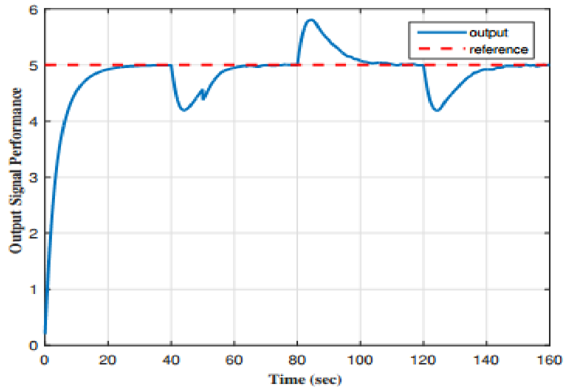

Fig. 6. Output and reference

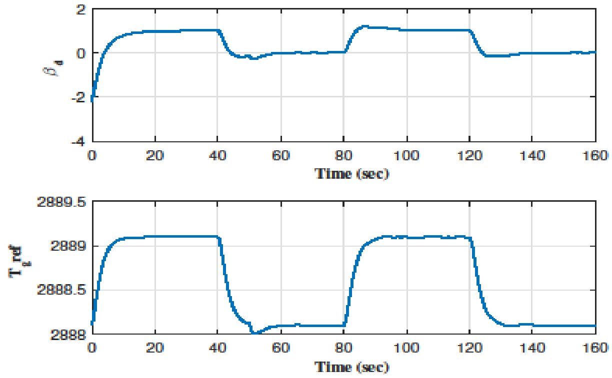

Fig. 7. Control signals

4.2. Sensor fault

Similar to the previous subsection, a periodic signal is used for modelling a sensor fault. One can obtain the gains of controller and observer as follows:

$$K = \begin{bmatrix} -1.1838 & -4.4732 & 0.0012 & 2.3169 \\ 0.001 & -0.002 & 0.002 & 0.001 \end{bmatrix} \tag{42}$$

$$L = \begin{bmatrix} 0.0002 & 0.4145 \\ 0.5055 & 0.8605 \\ 0.3573 & 162.69 \\ 0.0001 & -0.0001 \\ 0.8628 & -0.5032 \end{bmatrix}$$

With the aid of (42), the proposed FTC performance is examined under sensor fault. Fig. 8 shows that the fault estimation is successfully achieved. The responses of state estimations are depicted by Fig. 9. As shown in Fig. 10, the closed-loop system tolerates the faulty system since the control goal is realized. Also, the behaviour of control inputs is represented by Fig. 11. From Figs. 8-11, it can be concluded that the closed-loop FTC design has a satisfactory behaviour against sensor fault as well as the rotor speed tracking is provided during operation.

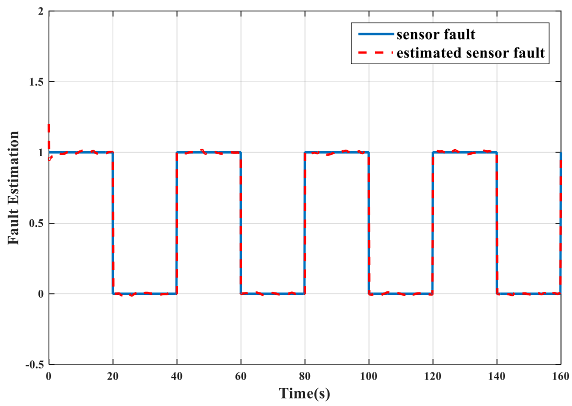

Fig. 8. Estimation of sensor fault

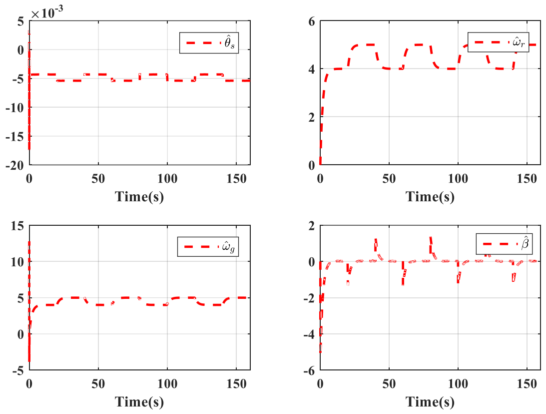

Fig. 9. Estimation of states

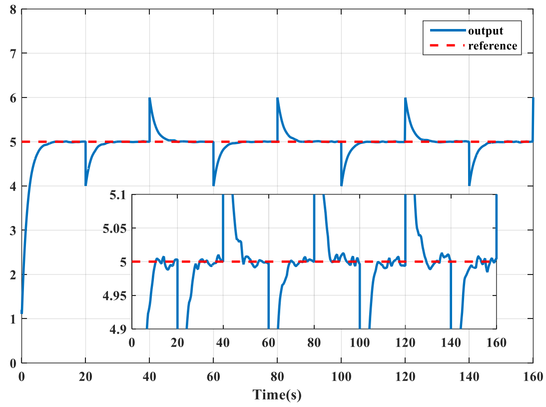

Fig. 10. Output and reference

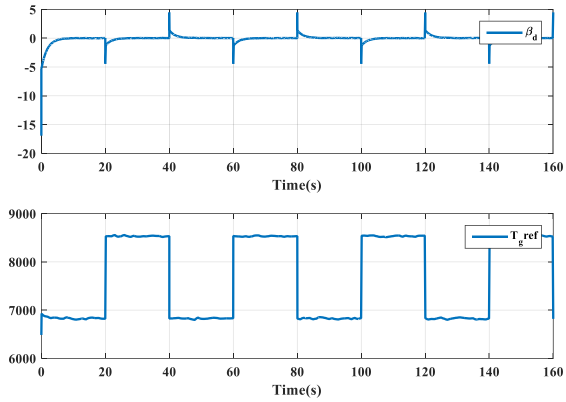

Fig. 11. Control signals

4.3. Comparison

To have a fair comparison, we adopted a robust LMI-based FTC design reported in (Bai et al., 2019) and redesigned for the wind turbine system described by (1) in the presence of sensor fault. It is worth noting that one can easily rewrite the wind turbine's model in the following form:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + f(x,t) \\ &\quad + Bd(t) + g(t) \\ y(t) &= Cx(t) + f_s(t) \end{aligned} \tag{43}$$

Therefore, the FTC controller is expressed as

$$\begin{aligned} u_{FTC}(t) &= -(\varepsilon + \bar{f}_s + \pi + \zeta(t) + \xi(t))\operatorname{sgn}(s_{\bar{x}}) \\ &\quad + K\hat{x}(t) \end{aligned} \tag{44}$$

in which

$$\begin{aligned} \zeta(t) &= \max\left\{ \| \hat{\bar{d}}(t) \|, \| \hat{\underline{d}}(t) \| \right\} \\ \xi(t) &= \left\{ \begin{aligned} &\| (GB)^{-1} GL_{p1} \bar{C}\, \bar{x}(t) \| \\ &+ \| (GB)^{-1} GL_{p1} \bar{C}\, \hat{\bar{x}}(t) \| \end{aligned} \right\} \end{aligned} \tag{45}$$

Besides, the sliding mode observer addressed in (Bai et al., 2019) has been proposed as

$$S\dot{z}(t) = \left(\bar{A} - \bar{L}_p\bar{C}\right)z(t) + \bar{B}u(t) + \bar{L}_s u_s(t) + \bar{L}_p y(t) + \bar{F}f(\hat{x},t) \tag{46}$$
$$\hat{x}(t) = z(t) + S^{-1}\bar{L}_N y(t)$$

More details are given in (Bai et al., 2019). For brevity, the definition of variables is omitted here (Please refer to the mentioned paper). Fig. 12 illustrates the tracking response of rotor speed based on the FTC-based design in (Bai et al., 2019). From Fig. 10 and Fig. 12, it is inferred that the output tracking error of our proposed method is smaller than one used in (Bai et al., 2019).

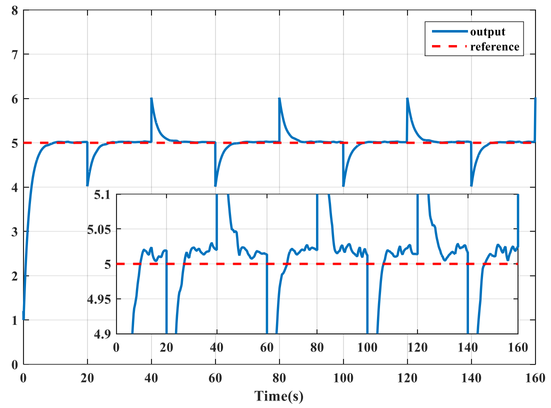

Fig. 12. Output and reference (Comparison mode)

To show the superiority of the proposed FTC to One addressed in (Bai et al., 2019), an effective criteria function is defined as

$$\gamma_{\omega_r} = \frac{\sum_{i=1}^{Ns} e_{FTC_{\omega_r}}}{\sum_{i=1}^{Ns} e_{\omega_r}} \tag{47}$$

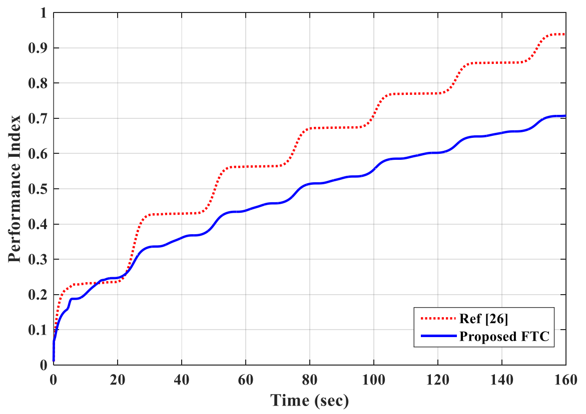

Fig. 13. Performance index (Comparison mode)

in which e_{ω_r} is the error of faulty rotor speed from the fault-free rotor speed while no FTC is applied, $e_{FTC_{\omega_r}}$ is the error of faulty rotor speed from the fault-free condition while FTC is activated in the control loop, and Ns is the number of samples during simulation. It can be deduced that $\gamma_{\omega_r} < 1$ shows an improvement in the FTC-based design. In other words, if the defined performance index of our proposed FTC become smaller than the comparison mode while it is lower than one, our proposed robust LMI-based has a better reflection against fault. As shown in Fig. 13, γ_{ω_r} is 0.705 in our Proposed FTC method while it is 0.935 in the design based on (Bai et al., 2019). As a result, we infer that the proposed FTC is more appropriate to deal with sensor fault in comparison with the mentioned paper.

5. CONCLUSION

In this paper, we studied a new robust controller for a wing turbine in the form of LMIs to estimate and tolerate the actuator/sensor fault occurred on the pitch system. The proposed FTC controller consists of an LQR base-line controller, a disturbance rejection term and the robust signal. The sufficient conditions were obtained to achieve the asymptotic stability of the entire system including the FTC controller and the observer. Numerical simulations illustrate the capability of the proposed method for a 1 MW wind turbine system.

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