Backstepping-based active fault tolerant control of wind turbine system using nonlinear fuzzy state observer

ALI BAKHSHI[1] AND ALIREZA ALFI[1,*]

[1] Faculty of Electrical and Robotic Engineering, Shahrood University of Technology, Shahrood, Iran
[*] Corresponding author: a_alfi@shahroodut.ac.ir

Manuscript received 16 December, 2019; revised 02 March, 2020, accepted 11 March, 2020. Paper no. JEMT-1912-1215.

Reliability and robustness are two main goals in developing control systems for wind turbine (WT) due to the existence of different sources, such as unknown malfunctions or faults. Their ignorance can significantly jeopardize the system performance and even stability. This paper presents a new active fault tolerant control (FTC) for WT system considering the fault of pitch system. The nonlinear model of WT is constructed in the form of strict-feedback in order to design an appropriate FTC-based backstepping control law. The mechanism of fault detection is based on a modified nonlinear fuzzy state observer, where the estimation of unknown terms is realized via fuzzy approximators, incorporated in the fuzzy observer. Accordingly, the rotor speed of the system can follow the desired reference in the presence of an actuator fault. The robust behavior, fast response, and acceptable tracking performance together with the model-free structure are the important properties of the proposed FTC-based controller. The stability of the overall closed-loop system, including the controller and the observer, is derived by the Lyapunov method. Simulation results highlight the superior performance of the proposed control method.

keywords: *Wind turbine, Fault tolerant control, Backstepping method, Fuzzy observer, Speed control, Stability proof.*

http://dx.doi.org/10.22109/jemt.2020.207326.1215

NOMENCLATURE

ω_r Rotor speed.

θ_s Train torsion angle.

ω_g Generator speed.

β Pitch angle.

k_s Drivetrain stiffness parameter.

d_s Drivetrain damping constant.

J_r Rotor inertia.

J_g Generator inertia.

τ_b Delay time constant for pitch dynamics.

K_i Parameters of observer.

r_i Design parameter of adaptive rules.

γ_i Learning rate parameter.

c_i Tuning parameter in control input.

θ_i Optimal parameter of FLS.

ϕ_i Fuzzy regressor.

1. INTRODUCTION

This is a painful reality that air pollution is increasing in the world by fossil energy productions [1]. Therefore, renewable energy plays a key a role in the power policies of many countries [2, 3]. Among the clean sources, wind energy has received much attention from researchers [4]. WT system encompasses a large part of world power production. To achieve high power generation, they are made on a large scale [5]. Accordingly, fault detection and tolerance are more important for the protection of its components in these systems [6]. Moreover, the repair and maintenance of the WT systems compared to power production are very expensive. Therefore, real time fault diagnosis and tolerance are most important issues. These systems are highly dependent on the environment. In the variable environmental conditions when the wind speed is changing, some problem is imposed on the system that, affects its performance. Some relevant works were focused on a constant speed while several studies were paid attention to the variable speed. Hence to achieve high efficiency, the existence of controllers is undeniable. However, many different control algorithms have been successfully reported in the literature to keep the power at a related interval for the WT systems, achieved by controlling the pitch angle [7]. Some of the appropriate controllers including PID control [8–11], LQG control [12, 13], robust control [14], gain scheduling [15], disturbance accommodation control [16], fuzzy logic control [17] and LPV control [18, 19], are considered as a base-line controller for WT system.

However, the occurrence of unknown malfunctions on the pitch actuator can be imposed serious barriers to the controller, so that may lead to instability of the system [20]. Therefore, using the active fault diagnosis and tolerant is a large requirement in WT systems that can be guaranteed the efficiency and stability of the system.

Various approaches have been proposed to deal with this problem. In [21], FDI algorithm based on identified fuzzy models was presented for the WT system. In addition, an uncertain TSK fuzzy based-model was exploited in which the FDI purpose was achieved by residual generation procedure. Applying the FDI methods for fault reconstruction is a complex manner due to the optimal residual production design, unknown time delay and uncertainty for the FTC system [22].

In general, FTC approaches are divided into two parts, namely the passive FTC (PFTC) and the active FTC (AFTC). The sliding-mode controller-based passive sensor FTC strategy was proposed in [23] to tolerate the generator speed sensor faults and generator torque offset faults. The aim of [19] is to present, an AFTC and PFTC pitch system with respect to the fault detection and fault isolation (FDI) for the system. In this study, FDI design to obtain the pitch actuator fault magnitude is unreachable or difficult. In [24], a state observer-based AFTC approach has been proposed for the linear parameter varying (LPV) model of wind turbine (WT), in which the faults were also estimated as well. The problem of pitch actuator failure was tackled by an AFTC approach using virtual actuator [25]. Furthermore , the linearized model was employed to build the state feedback control law for the nonlinear WT system.

In contrast with the pervious study, the PFTC has a robust behavior and also tackles to a specified class of faults or some level of uncertainty. Indeed, PFTC requires neither fault detection and diagnosis (FDD) scheme nor reconfigurable term. This is intended to apply to the fault-free system as well as faulty system. However, it has limited fault-tolerant capabilities and may cost nominal performance [26]. The main goal of any AFTC system is to ensure a dependable system. This system comprises two cascaded working modules, denoted as FDD and fault accommodation [27].

Besides, filters and observers have been widely examined during recent years to address state/fault estimation and control of dynamical systems [28–34]. Furthermore, great attention has been focused on sliding mode observers (SMO) for fault reconstruction and estimation (FRE) [35–38]. Recently, SMOs used for FRE and FTC of WT benchmark models [31, 32, 35, 36]. In [31], nominal pitch performance together with actuator fault tolerant was achieved by a traditional Proportional-Integral (PI) controller combined with a compensator. In [35], the reconstruction of the system against faults occurred in hydraulic pitch actuator and generator subsystems were provided based on a Takagi-Sugeno sliding mode observer with weighted switching action. In [36], sensor and actuator faults were reconstructed using the classic SMO. Estimation of faults in pitch angle sensors and actuators was obtained using physical redundancy of pitch sensors. However, the method was not robust against model uncertainties and disturbances. For this reason , a robust FRE scheme was proposed based on modified SMO to address the reconstruction of actuator and sensor faults of WT benchmark models [32]. Moreover, an FTC-based control law was developed for WT system in the presence of pitch actuator faults and sensor faults simultaneously [39].

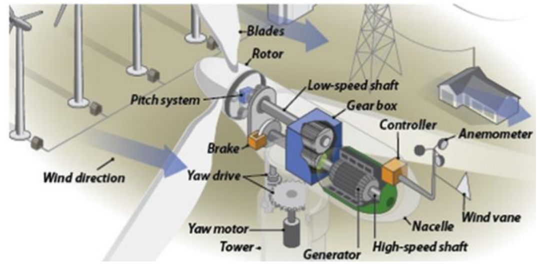

Fig. 1. The structure of WT.

Motivated by the previous observations, this paper presents a new AFTC scheme for WTs based on the backstepping method. With the aid of fuzzy approximators and fuzzy observer, the structure of the control system for this type of system is formed, where the stability of the closed-loop system against actuator fault is derived through the Lyapunov functions.

The remainder of this paper is structured as follows: The modeling of the system is presented in Section 2. The nonlinear fuzzy state observer is formulated in Section 3. The proposed FTC approach together with the stability proof is developed in Section 4. The simulation results are given in Section 5. Finally, Section 6 concludes the paper.

2. MODELING

A typical WT is depicted in Fig. 1. The nonlinear model of WT in the full load region is given as [40]:

$$\dot{\omega}_r = -\frac{k_s}{J_r}\theta_s - \frac{d_s}{J_r}\omega_r + \frac{d_s}{J_r}\omega_g + F\omega_r \tag{1}$$

$$\dot{\theta}_s = \omega_r - \omega_g \tag{2}$$

$$\dot{\omega}_g = \frac{k_s}{J_g}\theta_s + \frac{d_s}{J_g}\omega_r - \frac{d_s}{J_g}\omega_g \tag{3}$$

$$\dot{\beta} = -\frac{1}{\tau_b}\beta + \frac{1}{\tau_b}u \tag{4}$$

where the parameters of the system are presented later.

It is worth mentioning that the wind speed term is incorporated in F. The Eqs. (1)-(4) can be rewritten as:

$$\dot{x}_1 = -a_1x_2 - a_2x_1 + a_2x_3 + d_1\left(X,t\right) \tag{5}$$

$$\dot{x}_2 = x_1 - x_3 \tag{6}$$

$$\dot{x}_3 = a_3x_2 + a_4x_1 - a_4x_3 \tag{7}$$

$$\dot{x}_4 = -a_5x_4 + a_5u \tag{8}$$

$$y = x_1 \tag{9}$$

where

$$a_1 = \frac{k_s}{J_r},\ a_2 = \frac{d_s}{J_r},\ a_3 = \frac{k_s}{J_g},\ a_4 = \frac{d_s}{J_g},\ a_5 = \frac{1}{\tau_b} \tag{10}$$

It is straightforward to show Eqs. (5)-(8) in the following form:

$$\dot{x}_1 = f_1\left(X\right) + x_2 + d\left(X,t\right) \tag{11}$$

$$\dot{x}_2 = f_2(X) + x_3 \quad (12)$$

$$\dot{x}_3 = f_3(X) + x_4 \quad (13)$$

$$\dot{x}_4 = f_4(X) + \vartheta^T u \quad (14)$$

where $f_i, i = 1, \ldots, 4$ are:

$$f_1(X) = -a_1 x_2 - a_2 x_1 + a_2 x_3 - x_2 \quad (15)$$

$$f_2(X) = x_1 - 2x_3 \quad (16)$$

$$f_3(X) = a_3 x_2 + a_4 x_1 - a_4 x_3 - x_4 \quad (17)$$

$$f_4(X) = -a_5 x_4 \quad (18)$$

which are assumed to be unknown and will be estimated in the next section.

Remark 1: The fault of pitch system, considered in this study is consisted of lock-in-place and loss of effectiveness. Regarding the actuator fault, the input signal can be written as:

$$u = \rho v(t) + \sigma(\bar{u} - \rho v(t)) \quad (19)$$

where $v(t)$ is the applied control signal. Therefore, $\vartheta^T u$ is defined as $\vartheta^T \bar{u}_{lock} + \rho\vartheta^T b u_{0loss}$ (represented as j=i and $j \neq i$, respectively)

3. FUZZY STATE OBSERVER

One can define the following form for Eq. (4):

$$\begin{bmatrix} \dot{x}_1 \\ \vdots \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} -K_1 & 1 & 0 & 0 \\ -K_2 & 0 & 1 & 0 \\ -K_3 & 0 & 0 & 1 \\ -K_4 & 0 & 0 & 0 \end{bmatrix} X + \begin{bmatrix} K_1 \\ \vdots \\ K_4 \end{bmatrix} y + \sum_{i=1}^{4} B_i(f_i(X_i) + d_i) + B\vartheta^T u \quad (20)$$

Then, the fuzzy observer can be introduced as:

$$\begin{bmatrix} \dot{\hat{x}}_1 \\ \vdots \\ \dot{\hat{x}}_4 \end{bmatrix} = \begin{bmatrix} -K_1 & 1 & 0 & 0 \\ -K_2 & 0 & 1 & 0 \\ -K_3 & 0 & 0 & 1 \\ -K_4 & 0 & 0 & 0 \end{bmatrix} \hat{X} + \begin{bmatrix} K_1 \\ \vdots \\ K_4 \end{bmatrix} y + \sum_{i=1}^{4} B_i \hat{f}_i(X_i|\theta) + B\omega^T u$$
$$\rightarrow \ \dot{\hat{X}} = A\hat{X} + Ky + \sum_{i=1}^{4} B_i \hat{F}_i(\hat{X}|\theta) + B\vartheta^T u \quad (21)$$

The estimation error is defined as $e = X - \hat{X}$ and the Lyapunov function is expressed as $V_o = 0.5e^T Pe$. The time derivative of V_o is obtained as:

$$\dot{V}_o = 0.5\dot{e}^T Pe + 0.5e^T P\dot{e} = 0.5e^T\left(A^T P + PA\right)e + e^T P(\Delta f + \delta) + e^T P \sum_{i=1}^{4} B_i \tilde{\theta}_i^T \phi_i(\hat{X}_i) \quad (22)$$

Based on Young inequality, one can write:

$$e^T P(\Delta f + \delta) \le \left|e^T P\Delta f\right| + \left|e^T P\delta\right| \le 0.5\|P\|^2\|\delta^*\|^2 + \left(1 + 0.5\|P\|^2 \sum_{i=1}^{4} m_i^2\right)\|e\|^2 \quad (23)$$

$$e^T P \sum_{i=1}^{4} B_i \tilde{\theta}_i^T \phi_i(\hat{X}_i) \le n\tau\lambda_{max}^2(P)\|e\|^2 + \sum_{i=1}^{4} \frac{1}{\tau}\tilde{\theta}_i^T \tilde{\theta}_i \quad (24)$$

Thus,

$$\dot{V}_o \le -q\|e\|^2 + \frac{1}{2}\|P\|^2\|\delta^*\|^2 + \sum_{i=1}^{4} \frac{1}{\tau}\tilde{\theta}_i^T \tilde{\theta}_i \quad (25)$$

where $q = \lambda_{min}(Q) - \left(1 + 0.5\|P\|^2 \sum_{i=1}^{4} m_i^2 + n\tau\lambda_{max}^2(P)\right)$

4. BACKSTEPPING-BASED FTC

In this section, a new FTC is designed for the model of WT based on observer-based backstepping model-free approach. Define the first transformed variable as:

$$\chi_1 = y_1 - y_d \quad (26)$$

The time derivative of Eq. (26) can be written as:

$$\dot{\chi}_1 = \dot{y}_1 - \dot{y}_d = x_2 + F_1 + d - \dot{y}_d \quad (27)$$

Defining $e_2 = x_2 - \hat{x}_2$, one can have:

$$\dot{\chi}_1 = \hat{x}_2 + e_2 + f_1 + d - \dot{y}_d \quad (28)$$

Using fuzzy logic system, Eq. (28) can be expressed as:

$$\dot{\chi}_1 = \hat{x}_2 + e_2 + \theta_1^T \phi_{1(\hat{X})} + \tilde{\theta}_1^T \phi_1(\hat{X}) + \varepsilon_1 + \triangle F_1 + d - \dot{y}_d \quad (29)$$

For the first step of design, the Lyapunov function is defined as:

$$V_1 = V_o + \frac{1}{2}\chi_1^2 + \frac{1}{2\gamma_1}\tilde{\theta}_1^T \tilde{\theta}_1 \quad (30)$$

The time derivative of Eq. (30) is given by:

$$\dot{V}_1 \le -q\|e\|^2 + \chi_1\left(\chi_2 + \alpha_1 + \theta_1^T \Phi_1(\hat{X})\right) + \chi_1\varepsilon_1 + \chi_1 d + \chi_1\Delta F_1 + \chi_1 e_2 + \chi_1\tilde{\theta}_1^T \Phi_1(\hat{X}) - \frac{1}{\gamma_1}\tilde{\theta}_1^T \dot{\theta}_1 + \frac{1}{2}\|p\|^2\|\delta\|^2 + \frac{1}{\tau}\sum_{i=1}^{n} \tilde{\theta}_i^T \tilde{\theta}_i \quad (31)$$

One can suggest the first virtual input and the adaptation law as:

$$\alpha_1 = -c_1\chi_1 - 2\chi_1 - \theta_1^T \Phi_1(\hat{X})$$
$$\dot{\theta}_1 = \gamma_1\chi_1\Phi_1(\hat{X}) - r_1\theta_1 \quad (32)$$

Substituting Eq. (32) into Eq. (31) results in:

$$\dot{V}_1 \le -q_1 e^2 - c_1\chi_1^2 + \frac{r_1}{\gamma_1}\tilde{\theta}_1^T \theta_1 + \eta_1 + \frac{1}{\tau}\sum_{i=1}^{n} \tilde{\theta}_i^T \tilde{\theta}_i + \chi_1\chi_2 \quad (33)$$

The time derivative of χ_2 can be described as:

$$\dot{\chi}_2 = k_2 e_1 + \hat{x}_3 + \theta_2^T \Phi_2(\hat{X}) - \dot{\alpha}_1 - \ddot{y}_d + \tilde{\theta}_2^T \Phi_2(\hat{X}) - \tilde{\theta}_1^T \Phi_2(\hat{X}) \quad (34)$$

For this subsystem, the Lyapunov function is defined as:

$$V_2 = V_1 + \frac{1}{2}\chi_2^2 + \frac{1}{2\gamma_2}\tilde{\theta}_2^T \tilde{\theta}_2 \quad (35)$$

Regarding $\chi_3 = \hat{x}_3 - \alpha_2 - \ddot{y}_d$, one can obtain:

$$\begin{aligned} \dot{V}_2 \le & -q_1\|e\|^2 c_1\chi_1^2 + \tfrac{r_1}{\gamma_1}\tilde{\theta}_1^T\theta_1 + \eta_1 \\ & + \tfrac{1}{\tau}\sum_{i=1}^{n}\tilde{\theta}_i^T\tilde{\theta}_i + \chi_1\chi_2 + \\ & \chi_2\left(\chi_3 + \alpha_2 + \ddot{y}_d + k_2e_1 + \theta_2^T\Phi_2\left(\hat{X}\right) - \dot{\alpha}_1 - \ddot{y}_d + \tau\chi_2\right) \\ & + \tfrac{1}{\gamma_2}\tilde{\theta}_2^T\left(\gamma_2\chi_2\Phi_2\left(\hat{X}\right) - \dot{\theta}_2\right) + \tfrac{1}{\tau}\tilde{\theta}_2^T\tilde{\theta}_2 \end{aligned} \quad (36)$$

Thus, the second virtual input and the adaptation law can be suggested as:

$$\begin{aligned} \alpha_2 &= -c_2\chi_2 - \chi_1 + \dot{\alpha}_1 - \theta_2^T\Phi_2\left(\hat{X}\right) - k_2e_1 - \tau\chi_2 \\ \dot{\theta}_2 &= \gamma_2\chi_2\Phi_2\left(\hat{X}\right) - r_2\theta_2 \end{aligned} \quad (37)$$

Then, $\dot{V}_2$ is simplified as:

$$\begin{aligned} \dot{V}_2 \le & -q_1\|e\|^2 - c_1\chi_1^2 + \tfrac{r_1}{\gamma_1}\tilde{\theta}_1^T\theta_1 + \eta_1 \\ & + \tfrac{1}{\tau}\sum_{i=1}^{n}\tilde{\theta}_i^T\tilde{\theta}_i - c_2\chi_2^2 + \chi_2\chi_3\tfrac{r_2}{\gamma_2}\tilde{\theta}_2^T\theta_2 + \tfrac{1}{\tau}\tilde{\theta}_2^T\tilde{\theta}_2 \end{aligned} \quad (38)$$

The time derivative of χ_3 is obtained as:

$$\dot{\chi}_3 = k_3e_1 + \hat{x}_4 + \theta_3^T\Phi_3\left(\hat{X}\right) - \dot{\alpha}_2 - \dddot{y}_d \pm \tilde{\theta}_3^T\Phi_3\left(\hat{X}\right) \quad (39)$$

Now, the Lyapunov function can be written as:

$$V_3 = V_2 + \frac{1}{2}\chi_3^2 + \frac{1}{2\gamma_3}\tilde{\theta}_3^T\tilde{\theta}_3 \quad (40)$$

Considering the following relationships:

$$\begin{aligned} \chi_4 &= \hat{x}_4 - \alpha_3 - \dddot{y}_d \\ \chi_3\tilde{\theta}_3^T\Phi_3\left(\hat{X}\right) &\le \tau\chi_3^2 + \tfrac{1}{\tau}\tilde{\theta}_3^T\tilde{\theta}_3 \end{aligned} \quad (41)$$

One can explain the time derivative of Eq. (40) as:

$$\begin{aligned} \dot{V}_3 \le & -q_1\|e\|^2 - c_1\chi_1^2 - c_2\chi_2^2 + \chi_2\chi_3 + \tfrac{r_1}{\gamma_1}\tilde{\theta}_1^T\theta_1 \\ & + \eta_1 + \tfrac{1}{\tau}\sum_{i=1}^{n}\tilde{\theta}_i^T\tilde{\theta}_i + \tfrac{r_2}{\gamma_2}\tilde{\theta}_2^T\theta_2 + \tfrac{1}{\tau}\tilde{\theta}_2^T\tilde{\theta}_2 \\ & + \chi_3(\chi_4 + \alpha_3 + \dddot{y}_d + k_3e_1 + \theta_3^T\Phi_3\left(\hat{X}\right) - \dot{\alpha}_2 \\ & \quad - \dddot{y}_d + \tau\chi_3) \\ & + \tfrac{1}{\gamma_3}\tilde{\theta}_3^T\left(\gamma_3\chi_3\Phi_3\left(\hat{X}\right) - \dot{\theta}_3\right) + \tfrac{1}{\tau}\tilde{\theta}_3^T\tilde{\theta}_3 \end{aligned} \quad (42)$$

The third virtual input and the adaptation law is considered as:

$$\begin{aligned} \alpha_3 &= -c_3\chi_3 - \chi_2 + \dot{\alpha}_2 - k_3e_1 - \theta_3^T\Phi_3\left(\hat{X}\right) - \tau\chi_3 \\ \dot{\theta}_3 &= \gamma_3\chi_3\Phi_3\left(\hat{X}\right) - r_3\theta_3 \end{aligned} \quad (43)$$

Hence,

$$\begin{aligned} \dot{V}_3 \le & -q_1\|e\|^2 - c_1\chi_1^2 - c_2\chi_2^2 - c_3\chi_3^2 + \chi_3\chi_4 \\ & + \eta_1 + \tfrac{1}{\tau}\sum_{i=1}^{n}\tilde{\theta}_i^T\tilde{\theta}_i + \sum_{l=1}^{3}\tfrac{r_l}{\gamma_l}\tilde{\theta}_l^T\theta_l + \tfrac{1}{\tau}\sum_{j=2}^{3}\tilde{\theta}_j^T\tilde{\theta}_j \end{aligned} \quad (44)$$

For the last step of design, χ_4 is defined as:

$$\chi_4 = \hat{x}_4 - \alpha_3 - \dddot{y}_d \quad (45)$$

The time derivative of χ_4 is obtained as:

$$\begin{aligned} \dot{\chi}_4 &= k_4e_1 + \vartheta^T u + \theta_4^T\Phi_4\left(\hat{X}\right) - \dot{\alpha}_3 - y_d^{(4)} \\ &= k_4e_1 + \theta_4^T\Phi_4\left(\hat{X}\right) - \dot{\alpha}_3 - y_d^{(4)} + \sum_{j=}\vartheta_j\bar{u}_j \\ & + \sum_{j\neq i}\rho_j\vartheta_j b_j u_0 + \tilde{\theta}_4^T\Phi_4\left(\hat{X}\right) - \tilde{\theta}_4^T\Phi_4\left(\hat{X}\right) \end{aligned} \quad (46)$$

The final Lyapunov function is defined as:

$$V_4 = V_3 + \frac{1}{2}\chi_4^2 + \frac{1}{2\gamma_4}\tilde{\theta}_4^T\tilde{\theta}_4 \quad (47)$$

The time derivative of V_4 is calculated as:

$$\begin{aligned} \dot{V}_4 \le & -q_1e^2 - c_1\chi_1^2 - c_2\chi_2^2 - c_3\chi_3^2 + \chi_3\chi_4 \\ & + \eta_1 + \tfrac{1}{\tau}\sum_{i=1}^{n}\tilde{\theta}_i^T\tilde{\theta}_i + \sum_{l=1}^{3}\tfrac{r_l}{\gamma_l}\tilde{\theta}_l^T\tilde{\theta}_l + \tfrac{1}{\tau}\sum_{j=2}^{3}\tilde{\theta}_j^T\tilde{\theta}_j \\ & + \chi_4(\sum_{j=i}\vartheta_j\bar{u}_j + \sum_{j\neq i}\rho_j\vartheta_j b_j u_0 + k_4e_1 + \theta_4^T\Phi_4\left(\hat{X}\right) \\ & \quad - \dot{\alpha}_3 - y_d^{(4)} + \tau\chi_4) \\ & + \tfrac{1}{\gamma_4}\tilde{\theta}_4^T\left(\gamma_4\chi_4\Phi_4\left(\hat{X}\right) - \dot{\theta}_4\right) + \tfrac{1}{\tau}\tilde{\theta}_4^T\tilde{\theta}_4 \end{aligned} \quad (48)$$

Finally, the control input and the last adaptation law is proposed as:

$$\begin{aligned} \dot{\theta}_4 &= \gamma_4\chi_4\Phi_4\left(\hat{X}\right) - r_4\theta_4 \\ u_0 &= \left(\sum_{j\neq i}\rho_j\vartheta_j b_j\right)^{-1}[-\chi_3 - c_4\chi_4 - k_4e_1 \\ & -\theta_4^T\Phi_4\left(\hat{X}\right) + \dot{\alpha}_3 + y_d^{(4)} - \tau\chi_4 - \sum_{j=j_1,..}\vartheta_j\bar{u}_j] \end{aligned} \quad (49)$$

Substituting Eq. (49) into Eq. (48), one can obtain:

$$\begin{aligned} \dot{V}_4 \le & -q_1\|e\|^2 - \sum_{l=1}^{4}c_l\chi_l^2 + \eta_1 + \tfrac{2}{\tau}\sum_{i=2}^{4}\tilde{\theta}_i^T\tilde{\theta}_i \\ & + \tfrac{1}{\tau}\tilde{\theta}_1^T\tilde{\theta}_1 + \tfrac{r_1}{\gamma_1}\left(-\tfrac{1}{2}\tilde{\theta}_1^T\tilde{\theta}_1 + \tfrac{1}{2}\theta_1^{*^T}\theta_1^*\right) \\ & + \sum_{i=2}^{4}\tfrac{r_i}{\gamma_i}\left(-\tfrac{1}{2}\tilde{\theta}_l^T\tilde{\theta}_l\right) + \sum_{i=2}^{4}\tfrac{r_i}{2\gamma_i}\theta_l^{*^T}\theta_l^* \end{aligned} \quad (50)$$

Equation Eq. (50) can be written as:

$$\dot{V}_f \le -AV_f + \zeta \quad (51)$$

where $V_f = V_4$ and

$$\zeta = \sum_{i=2}^{4}\frac{r_i}{2\gamma_i}\theta_l^{*^T}\theta_l^* + \eta_1 \quad (52)$$

Therefore, the stability of the FTC-based backstepping is confirmed using the Lyapunov function.

5. SIMULATION RESULTS

This section includes different cases to indicate the effectiveness of the proposed controller using MATLAB 2017b software. The tuning parameters are itemized in Table 1. The controller is tested for random variation of wind profile around the speed of 12 units, as shown in Fig. 2. The control goal is to achieve the rotor speed to the 1.27 *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.

Case 1: without fault

Table 1. The tuning parameters

Parameters	Values
K	[1 1 5 5]
c	[6 6 12 9]
γ	[50 10 20 20]
r	[0.1 0.1 0.1 0.1]
τ	0.2
φ	0.6

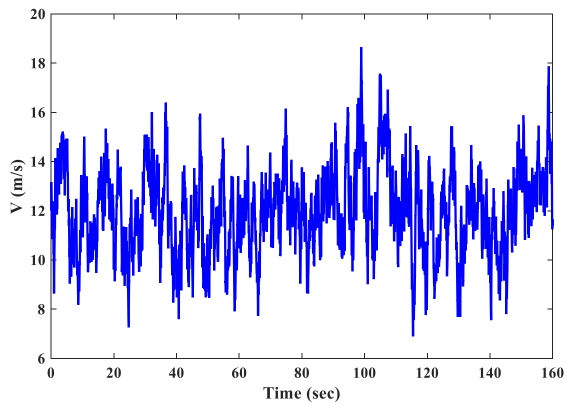

Fig. 2. The wind speed.

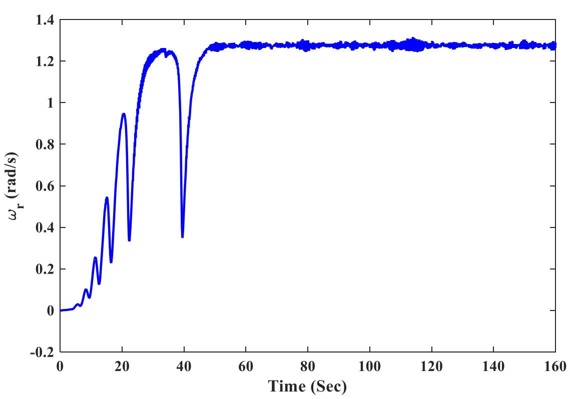

Fig. 3. The rotor speed (Case 1).

In this experiment, the performance of the proposed method is analyzed without the effect of fault. As shown in Fig. 3, the tracking of rotor speed is achieved as well. Fig. 4 depicts the control signal behavior. The Fig. 5 indicates the performance of the nonlinear state fuzzy observer in estimating the states. From Fig. 5, it can be concluded that the estimation of rotor speed follows the reference as well. The rest of estimations are also converged to a constant value accordingly.

Case 2: faulty without FTC The fault occurs in the actuator of the WT as shown in Fig. 6. This experiment illustrates the system performance against fault without compensating signal as shown in Fig. 7. This figure demonstrates that the performance of the closed-loop system is affected by the fault. Generally, the efficiency of the system is not reasonable.

Case 3: AFTC Here, the performance of the proposed FTC is evaluated under actuator fault. Fig. 8, shows that the proposed method tolerates the faulty system. Furthermore, Fig. 9 represents the behavior of the control input. The response of the fuzzy observer is also given in Fig. 10. It can be concluded that the behavior of the closed-loop system is better in comparison with the results of the experiment 1 and the fault tolerant goal is successfully achieved.

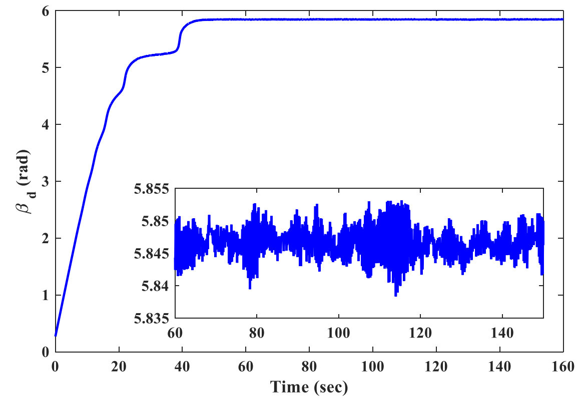

Fig. 4. The control signal (Case 1).

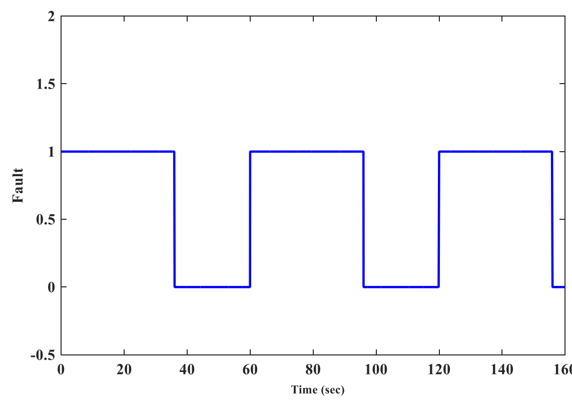

Fig. 6. The shape of fault.

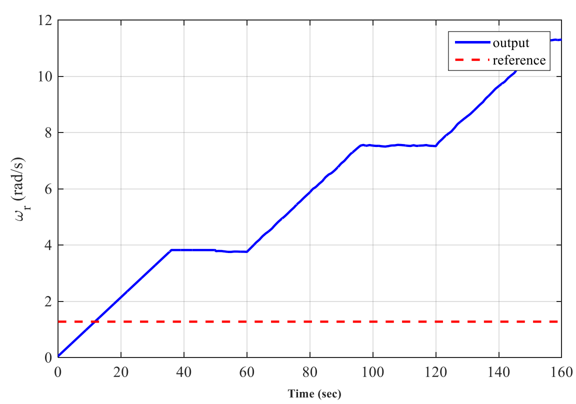

Fig. 7. The rotor speed (output, Case 2).

6. CONCLUSION

The purpose of this paper was to present a nonlinear fuzzy state observer-based adaptive backstepping approach for the WT system, where the pitch actuator was considered in the control

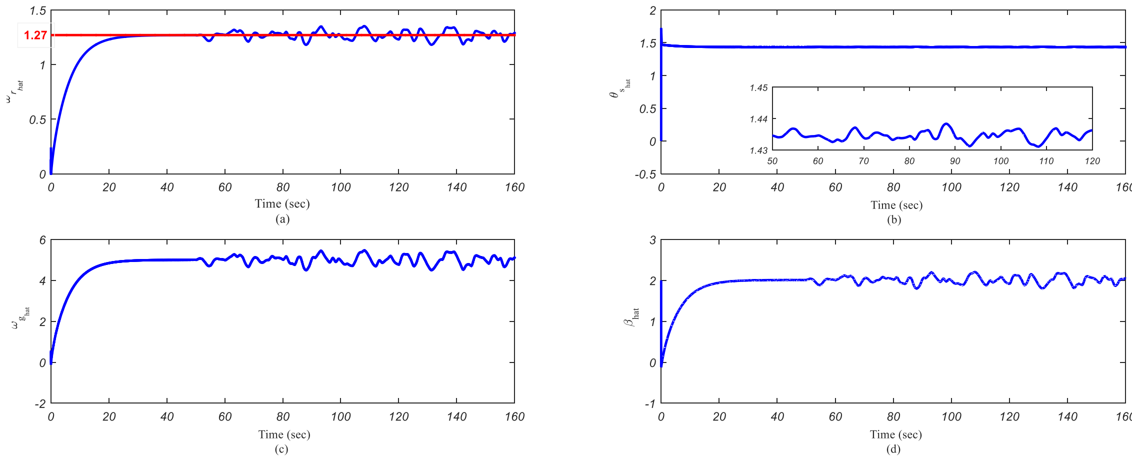

Fig. 5. State estimations (Case 1): (a) Rotor speed (b) Train torsion angle (c) Generator speed (d) Pitch angle.

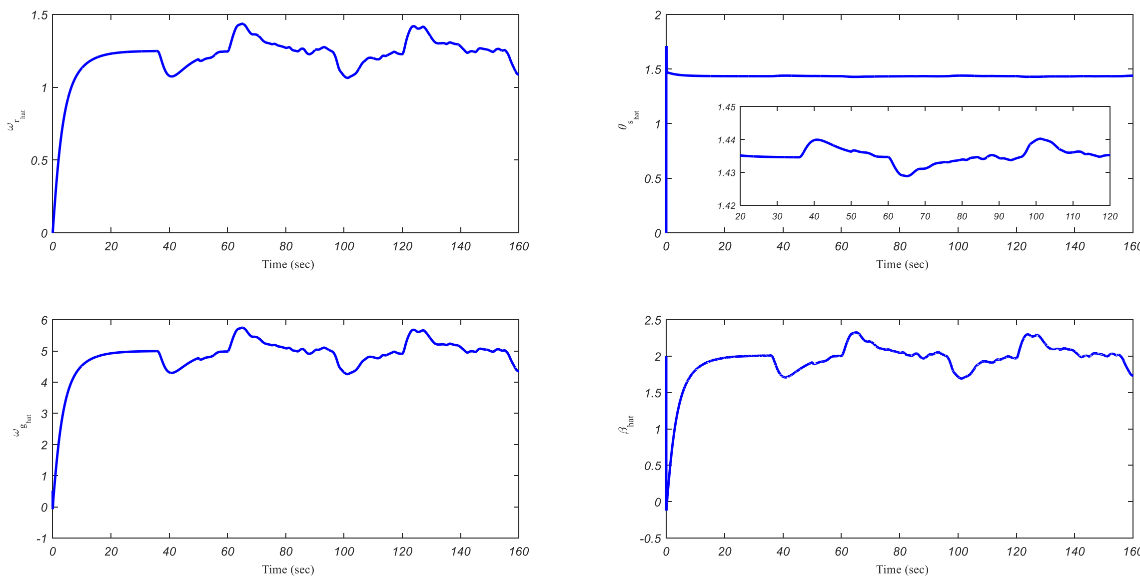

Fig. 10. State estimations (Case 3) (a) Rotor speed (b) Train torsion angle (c) Generator speed (d) Pitch angle.

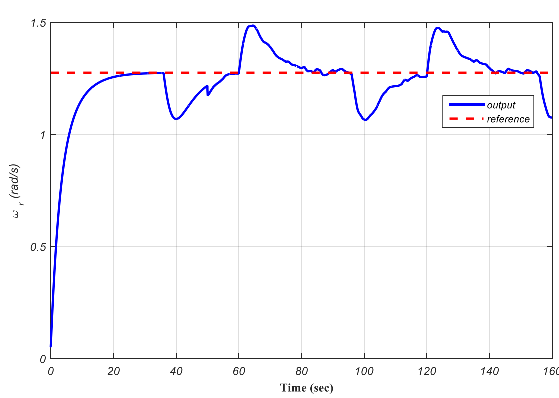

Fig. 8. The response of FTC design (Case 3).

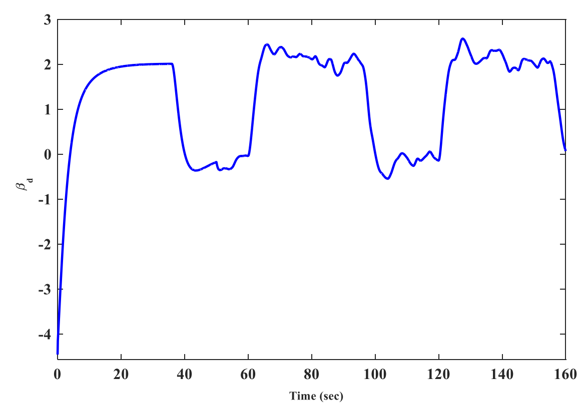

Fig. 9. The control signal (Case 3).

loop which was compensated in the framework of the control design. In addition, the state observer was designed to estimate the state vector. With the help of backstepping method, the stability of the observer together with the proposed controller was guaranteed by the Lyapunov theorem. The reliability of the control system was also ensured by proposing a modified FTC design in the presence of wind speed as an external disturbance. Finally, different experiments were carried out to illustrate the efficiency of the proposed control strategy in terms of accuracy and robustness against malfunctions.

Future Work

Future work in this area is to propose a new FTC including fault estimation based on Kalman filter.

REFERENCES

1. K. Uddin, "Nuclear energy, environment and public safety: north-south politics," Strategic Planning for Energy and the Environment, vol. 38, pp. 31-41, 2019.
2. M. Hemmati, "Risk-based optimal scheduling of reconfigurable smart renewable energy-based microgrids," International Journal of Electrical Power & Energy Systems, vol. 101 pp. 415-428, 2018.
3. M. Ghahramani, "Energy and reserve management of a smart distribution system by incorporating responsive-loads/battery/wind turbines considering uncertain parameters," Energy, 2019.
4. G. Wang, and H. Zenghui, "Data-driven fault-tolerant control design for wind turbines with robust residual generator," IET Control Theory & Applications, vol. 9, pp. 1173-1179, 2015.
5. P. Kanjiya, B. Ambati, and V. Khadkikar, "A novel fault-tolerant DFIG-based wind energy conversion system for seamless operation during grid faults," IEEE Transactions on Power Systems, vol. 29, pp. 1296-1305, 2013.
6. S. Abdelmalek, B. Linda, and A. Larabi, "An advanced robust fault-tolerant tracking control for a doubly fed induction generator with actuator faults," Turkish Journal of Electrical Engineering & Computer Sciences, vol. 25, pp. 1346-1357, 2017.
7. Wu, Dinghui, "Fault estimation and fault-tolerant control of wind turbines using the SDW-LSI algorithm." IEEE Access, vol. 4, pp. 7223-7231, 2016.
8. T. Burton, N. Jenkins, D. Sharpe, E. Bossanyi, Wind Energy Handbook, John Wiley & Sons, 2011.
9. M. M. Hand, "Variable-speed wind turbine controller systematic design methodology: a comparison of non-linear and linear model-based designs," Tech. rep., National Renewable Energy Lab., Golden, CO (US) (1999).
10. B. Boukhezzar, L. Lupu, H. Siguerdidjane, M. Hand, "Multivariable control strategy for variable speed, variable pitch wind turbines," Renewable Energy, vol. 32, pp. 1273–1287, 2007.
11. R. Gao, Z. Gao, "Pitch control for wind turbine systems using optimization, estimation and compensation," Renewable Energy, vol. 91, pp. 501–515, 2016.
12. P. Novak, T. Ekelund, I. Jovik, B. Schmidtbauer, "Modeling and control of variable-speed wind-turbine drive-system dynamics," IEEE Control Systems, vol. 15, pp. 28–38, 1995.
13. K. Stol, L. Fingersh, "Wind turbine field testing of state-space control designs," National Renewable Energy Laboratory, NREL/SR-500-35061, Golden, Co.
14. H. Geng, G. Yang, "Output power control for variable-speed variable-pitch wind generation systems," IEEE Transactions on Energy Conversion, vol. 25, pp. 494–503, 2010.
15. F. Bianchi, R. Mantz, C. Christiansen, "Gain scheduling control of variable speed wind energy conversion systems using quasi-LPV models," Control Engineering Practice, vol. 13, pp. 247–255, 2005.
16. K. A. Stol, M. J. Balas, "Periodic disturbance accommodating control for blade load mitigation in wind turbines," Journal of solar energy engineering, vol. 125, pp. 379–385, 2003.
17. A. Z. Mohamed, M. N. Eskander, F. A. Ghali, "Fuzzy logic control based maximum power tracking of a wind energy system," Renewable energy, vol. 23, pp. 235–245, 2001.
18. C. Sloth, T. Esbensen, J. Stoustrup, "Robust and fault-tolerant linear parameter-varying control of wind turbines," Mechatronics, vol. 21, pp. 645–659, 2011.
19. F. Shi, R. Patton, "An active fault tolerant control approach to an offshore wind turbine model," Renewable Energy, vol. 75, pp. 788–798, 2015.
20. A. Justin, and S. Reshma, "Fault tolerant control of wind energy conversion system—Fuzzy approach," 2013 Fourth International Conference on Computing, Communications and Networking Technologies (ICCCNT). IEEE, 2013.
21. S. Simani, S. Farsoni, P. Castaldi, "Fault diagnosis of a wind turbine benchmark via identified fuzzy models," IEEE Trans. Ind.Electron. vol. 62, pp. 3775–3782, 2015.
22. J. Lan, R. J. Patton, "A new strategy for integration of fault estimation within fault-tolerant control," Automatica, vol. 69, pp. 48–59, 2016.
23. M. Sami, and J.P. Ron, "Fault tolerant adaptive sliding mode controller for wind turbine power maximisation," IFAC Proceedings Volumes, vol. 45, 499-504, 2012.
24. F. Shi, R. Patton, "An active fault tolerant control approach to an offshore wind turbine model," Renew. Energy., vol. 78 pp. 788–19, 2015.
25. D. Wu, J. Song, Y. Shen, Z. Ji, "Active fault-tolerant linear parameter varying control for the pitch actuator of wind turbines," Nonlinear Dyn. vol. 87, pp. 475–487, 2016.
26. H. Badihi, Z. Youmin, and H. Hong, "Wind turbine fault diagnosis and fault-tolerant torque load control against actuator faults," IEEE Transactions on Control Systems Technology, vol. 23, pp. 1351-1372, 2014.
27. T. Jain, J.Y. Joseph, and S. Dominique, "A novel approach to real-time fault accommodation in NREL's 5-MW wind turbine systems," IEEE Transactions on Sustainable Energy, vol. 4, pp. 1082-1090, 2013.
28. B. Xiao, S. Yin, and H. Gao, "Reconfigurable tolerant control of uncertain mechanical systems with actuator faults: A sliding mode observer-based approach," IEEE Trans. Control Syst. Technol., 2017.
29. B. Xiao, S. Yin, "Exponential tracking control of robotic manipulators with uncertain kinematics and dynamics," IEEE Trans. Ind. Informatics., 2018.
30. L. Cao, D. Qiao, and X. Chen, "Huber based cubature Kalman filter for attitude estimation of small satellite," Acta Astronaut. vol. 148, pp. 48–56, 2018.
31. J. Lan, R.J. Patton, and X. Zhu, "Fault-tolerant wind turbine pitch control using adaptive sliding mode estimation," Renew. Energy. vol. 116, pp. 219–231, 2018.
32. M. Rahnavard, M. Ayati, and M.R. Hairi-Yazdi, "Robust actuator and sensor fault reconstruction of wind turbine using modified sliding mode observer," Trans. Inst. Meas. Control., 2018.
33. J.Y. Ng, C.P. Tan, H. Trinh, and K.Y. Ng, "A common functional observer scheme for three systems with unknown inputs," J. Franklin Inst. vol. 353, pp. 2237–2257, 2016.
34. M. Ayati, F.R. Salmasi, "Fault detection and approximation for a class of linear impulsive systems using sliding-mode observer," Int. J. of Adap. Cont. and Signal Processing. vol. 29, pp. 1427-1441, 2015.
35. W. S. Chua, C.P. Tan, M. Aldeen, and S. Saha, "A robust fault estimation scheme for a class of nonlinear systems," Asian J.Control. vol. 19, pp. 799–804, 2017.
36. X. Wang, C.P. Tan, and D. Zhou, "A novel sliding mode observer for state and fault estimation in systems not satisfying matching and minimum phase conditions," Automatica. vol. 79, pp.290–295, 2017.
37. J.H.T. Ooi, C.P. Tan, W.-S. Chua, and X. Wang, "State and unknown input estimation for a class of infinitely unobservable descriptor systems using two observers in cascade," J. Franklin Inst. vol. 354, 8374–8397, 2017.
38. J.H.T. Ooi, C.P. Tan, S.G. Nurzaman, and K.Y. Ng, "A sliding mode observer for infinitely unobservable descriptor systems," IEEE Trans. Automat. Contr. vol. 62, pp. 3580–3587, 2017.
39. P.F. Odgaard, J. Stoustrup, and M. Kinnaert, "Fault tolerant control of wind turbines – a benchmark model," in: 7th IFAC Symp.Fault Detect. Superv. Saf. Tech. Process., 2009.
40. Kühne, Patrick, Florian Pöschke, and Horst Schulte, "Fault estimation and fault-tolerant control of the FAST NREL 5MW reference wind turbine using a proportional multi-integral observer," International Journal of Adaptive Control and Signal Processing, vol. 32, pp. 568-585, 2018.