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Active Fault Tolerant Control of Wind Turbine Systems using Disturbance Observer-based Sliding Mode and Time Delay Estimation

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ABSTRACT: In this paper, an active fault tolerant control based on time delay control, sliding mode, and nonlinear disturbance observer is proposed to control the pitch subsystem in the presence of actuator faults and uncertainties. Time delay estimation is applied as a fault estimation algorithm for detection and compensation. Then, a robust control law is synthesized to nullify uncertainty and fault effects using a combination of sliding mode, disturbance observer, and time delay with novel adaptation laws. In order to mitigate chattering which comes from the discontinuous control term, a nonlinear disturbance observer is designed. Through the proposed structure, the discontinuous gain is reduced significantly which leads to chattering reduction. Stability analysis is conducted through Lyapunov Theory. Moreover, wind speed profiles are generated using TurbSim, and simulations are performed based on a nonlinear two-mass wind turbine model and implemented in the FAST environment to verify the validity of the designed controllers. Finally, results reveal the effectiveness of the proposed controller compared to feedback linearization and gain-schedule proportional-integral controllers in the presence of uncertainty and different actuator faults such as hydraulic leakage, pump wear, and high air content in the oil.

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1. INTRODUCTION

Wind turbines, as the main wind energy conversion system, have complex and nonlinear dynamics and work in uncertain environments under large turbulent winds and centrifugal, gravitational, and gyroscopic loads [1]. To prevent unpredicted failures, maintenance schedules are planned, which not only increase cost but also reduce the power generation due to required downtime [2]. Various approaches have been proposed to solve the fault detection and fault tolerant control problem of wind turbines. In [3] an Active Fault Tolerant Control (AFTC) was designed to control rotor speed and power of a wind turbine in the presence of actuator faults and uncertainties. The control scheme was a Sliding Mode Control (SMC) with an integral surface and an adaptive gain, termed as adaptive output feedback sliding mode controller. In [4], fault detection and Fault Tolerant Control (FTC) for pitch actuator fault using a disturbance compensator and a discrete control structure was proposed. To validate the effectiveness of the proposed FTC approach, this structure was implemented in the FAST environment.

To the best of the authors' knowledge, none of the published papers in the realm of wind turbine control have studied the effects of pitch actuator fault such as hydraulic leakage, pump wear, and high air content in the oil for collective pitch angle control based on nonlinear model. Then, this paper proposes a novel AFTC based on Time Delay Estimation (TDE) and Nonlinear Disturbance Observer (NDO) for wind turbine systems to nullify the effects of actuator and sensor faults, uncertainties, and exogenous disturbances.

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2. PROBLEM STATEMENT

This paper uses Controls Advanced Research Turbine (CART) located at National Renewable Energy Laboratory (NREL) USA. By choosing the state and input vectors as $x(t)=\begin{bmatrix}\omega_r & \omega_g & \delta & \beta\end{bmatrix}^T$, and $u=\beta_r$, then the affine system can be expressed as $\dot{x}(t)=f(x)+gu$. For hydraulic pitch control systems, each actuator is considered as a linear second-order system with the following transfer function.

$$\frac{\beta}{\beta_r}=\frac{\omega_n{}^2}{s^2+2\zeta\omega_n s+\omega_n{}^2} \tag{1}$$

where β_r, ζ and ω_n introduce the reference pitch angle, damping ratio, and natural frequency, respectively.

2.1 Problem formulation

It can be proved that there exists a diffeomorphism transformation so that the wind turbine dynamics is equivalent to the system in its normal form with stable zero dynamics. Thus, the second-order derivative of rotor speed dynamics is written as,

$$\ddot{x}_1 = L_f + L_g u \tag{2}$$

Where L_f and L_g are nonlinear terms.

2.2 AFTC based on SMC-NDO and TDE

In this section, an AFTC is proposed using SMC-NDO and TDE. to compensate for the effects of faults, uncertainties, and exogenous disturbances. According to the SMC theory, the sliding surface is defined as:

$$S = \dot{e}(t) + k_p e(t) + k_i \int e(t)dt \tag{3}$$

Taking the time derivative of Eq. (8) and by some mathematical simplification, the SMC law can be derived. In order to estimate the external disturbance, a nonlinear disturbance observer is designed as

$$\begin{aligned} \dot{z} &= -\lambda z - \lambda\left[\lambda\dot{\omega}_r + L_f + L_g u\right] \\ \hat{d} &= z + \lambda\dot{\omega}_r \end{aligned} \tag{4}$$

where z and κ represent the internal state of the observer and the observer gain ($\kappa >$ ·). Now, the control law can be rewritten as:

$$u_{SM-NDO} = \frac{-1}{L_g}\left(k_p\dot{e} + k_i e + L_f + \hat{d} - K\,\mathrm{sgn}(S)\right) \tag{5}$$

Assumption 1. the estimation error of the exogenous disturbance is bounded.

It can be assumed that the uncertainty and actuator fault can be lumped in the following term:

$$\begin{aligned} \Delta_r(x,\dot{x},u)_t &\cong \Delta_r(x,\dot{x},u)_{t-\tau} \\ \Phi_r(x,\dot{x},u)_t &\cong \Phi_r(x,\dot{x},u)_{t-\tau} \end{aligned} \tag{6}$$

By adding these two approximate functions and replacing their equivalent values from Eq. (6), the following TDE is obtained.

$$\begin{aligned} &\hat{\Delta}_r(x,\dot{x},u)_t + \hat{\Phi}_r(x,\dot{x},u)_t \triangleq \\ &\Delta_r(x,\dot{x},u)_{t-\tau} + \Phi_r(x,\dot{x},u)_{t-\tau} = \\ &\ddot{x}_{1_{t-\tau}} - L_{f_{t-\tau}} - L_{g_{t-\tau}} u_{t-\tau} = \Re_{TDE} \end{aligned} \tag{7}$$

It is assumed that the uncertainties and faults can be expressed as $\Delta_r(x,\dot{x},u) + \Phi_r(x,\dot{x},u) = \Re_{TDE} + \upsilon$, where υ is the TDE error. Then, the rotor speed dynamics in the presence of fault and uncertainty can be rewritten as,

$$\ddot{x}_1 = L_f + L_g u + d + \Re_{TDE} + \upsilon \tag{8}$$

Assumption 2: the TDE error has an upper bound and $|\upsilon| \le \bar{\upsilon}$.

The control law for the AFTC is obtained as,

$$u_{AFTC} = \frac{-1}{L_g}\left(\begin{aligned}&\left(k_p\dot{e} + k_i e + L_f + \hat{d}\right) \\ &+\Re_{TDE} + (K + \bar{\upsilon})\,\mathrm{sgn}(S)\end{aligned}\right) \tag{9}$$

Theorem 2: Considering the sliding surface, Eq. (3), the nonlinear disturbance observer, Eq. (4), and the designed AFTC law, Eq. (9), for the wind turbine, asymptotical stability can be achieved, despite unknown external disturbances and parametric uncertainties if the discontinuous gain is chosen as $K \ge \eta + E_d + \bar{\upsilon}$.

Proof: A positive definite Lyapunov function is chosen as $V = \frac{1}{2}(S^2 + \tilde{d}^2)$. Taking time derivative:

$$\begin{aligned} \dot{V} &= S\dot{S} + \tilde{d}\dot{\tilde{d}} \\ &= \left[S\left(-(K + \bar{\upsilon})\,\mathrm{sgn}(S) + \tilde{d} + \upsilon\right) - \lambda\tilde{d}^2\right] \\ &\le \left[|S|\left(\left(\bar{\upsilon} - K - \bar{\upsilon}\right) + \tilde{d}\right) - \lambda\tilde{d}^2\right] \\ &\le \left[-K|S| - \lambda\tilde{d}^2\right] \end{aligned} \tag{10}$$

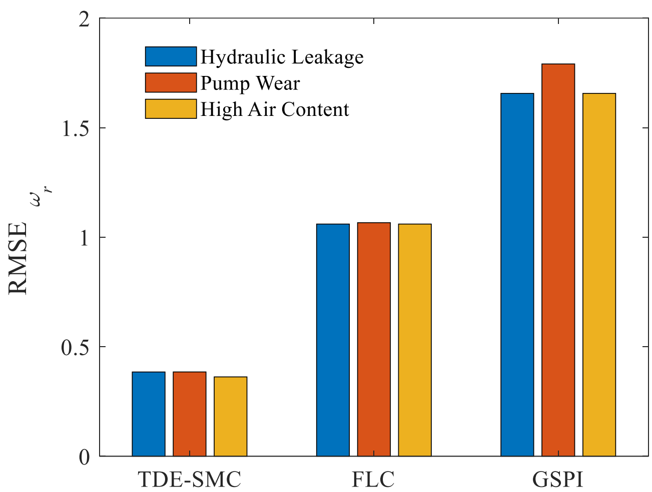

Fig. 1. RMSE of rotor speed in the presence of different faults

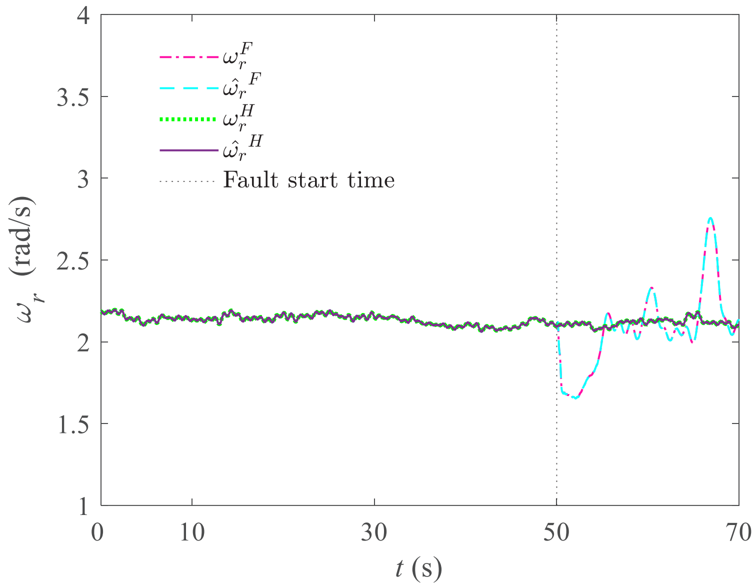

Fig. 2. Rotor speed for both healthy and faulty conditions

Then, the reachability condition is satisfied. Rotor speed is estimated using a super-twisting sliding mode observer.

3. RESULTS AND DISCUSSION

For simulation, hydraulic leakage on the pitch actuator is considered in the system. The proposed AFTC is applied on a two-mass model and to verify the validity of this control scheme, the control law is implemented in the FAST environment. To apply realistic turbulent wind fields, IEC Kaimal spectral model with different intensities is extracted from TurbSim. The Root Mean Square (RMS) Error of rotor speed for the wind turbine with the AFTC exposed to various wind profiles is shown in Fig.1. The results clearly prove the outperformance of the AFTC and this is more evident for higher wind speeds.

Fig. 2 shows the rotor speed response. It is obvious that the proposed AFTC is successfully capable of addressing the adverse effects of fault, uncertainty, and disturbance.

4. CONCLUSION

This paper aimed to present a novel AFTC based on TDE to control the pitch angle of a wind turbine in the presence of faults, uncertainties, and disturbances. The proposed AFTC comprises a TDE-based FD system and a combination of SMC and NDO. The stability of the closed-loop system was proved by Lyapunov theory. In order to verify the validity of the proposed controller, it was applied to the detailed FAST simulator for two distinct cases, i.e. faulty and healthy conditions. Simulations revealed the effectiveness of the proposed AFTC. Overall, compared with the existing schemes, the proposed AFTC possesses some advantages and improvements including, easy implementation of the proposed TDE-based FD system, fast finite time convergence, and higher precision due to applying the supper-twisting algorithm, compensating uncertainties and faults, and independence from the prior knowledge of the faults.

REFERENCES

[1] B. Boukhezzar, L. Lupu, H. Siguerdidjane, M. Hand, Multivariable control strategy for variable speed, variable pitch wind turbines, Renewable Energy, 32(8) (2007) 1273-1287.

[2] A. Azizi, H. Nourisola, S. Shoja-Majidabad, Fault tolerant control of wind turbines with an adaptive output feedback sliding mode controller, Renewable Energy 135 (2019) 55-65.

[3] H. Habibi, I. Howard, S. Simani, Reliability improvement of wind turbine power generation using model-based fault detection and fault tolerant control: A review, Renewable Energy 135 (2019) 877-896.

[4] Y. Vidal, C. Tutivén, J. Rodellar, L. Acho, "Fault diagnosis and fault-tolerant control of wind turbines via a discrete time controller with a disturbance compensator", Energies, 8(5) (2015) 4300-4316.

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