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An active fault tolerant control approach to an offshore wind turbine model

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ABSTRACT

The paper proposes an observer based active fault tolerant control (AFTC) approach to a non-linear large rotor wind turbine benchmark model. A sensor fault hiding and actuator fault compensation strategy is adopted in the design. The adapted observer based AFTC system retains the well-accepted industrial controller as the baseline controller, while an extended state observer (ESO) is designed to provide estimates of system states and fault signals within a linear parameter varying (LPV) descriptor system context using linear matrix inequality (LMI). In the design, pole-placement is used as a time-domain performance specification while H_∞ optimization is used to improve the closed-loop system robustness to exogenous disturbances or modelling uncertainty. Simulation results show that the proposed scheme can easily be viewed as an extension of currently used control technology, with the AFTC proving clear "added value" as a fault tolerant system, to enhance the sustainability of the wind turbine in the offshore environment.

1. Introduction

As an economically, socially as well as ecologically sustainable renewable energy, wind energy [1] is attracting more and more attention along with the increasing awareness of the need to protect the global environment and in view of the depletion of fossil resources. As a result, wind turbines are contributing more and more to energy production [2] as shown in Fig 1, along with the increasing size of the standard wind turbine systems.

Large rotor wind turbines installed recently are expensive and far from living zones, often offshore escalating the requirements of safety, reliability and maintainability [3–7]. An attractive candidate solution is to introduce fault detection and isolation (FDI) and fault tolerant control (FTC) techniques since the control system play an important role in the operation of the wind turbine [8–10] and different control strategies may be considered for different wind turbines systems. In the light of these developments there have been two benchmark models presented in Refs. [11,12] to design robust fault detection and FTC systems for modern large rotor wind turbines; Based on the two models, many results have been presented such as the results presented in Refs. [13–17]. The fault tolerant control strategy in Ref. [14] considers the low wind speed region using a T-S fuzzy modelling approach while the approach in Ref. [15] considers the high speed wind region using a geometric approach. A fault detection and isolation system for rotor current sensors in a doubly-fed induction generator for wind turbine applications is presented in Ref. [16] based on the generalized observer scheme. However, none of these studies consider the robustness of the closed-loop system. On the other hand, in Ref. [17] the closed-loop robustness is studied, albeit only for the low wind speed region, considering sensor fault tolerance.

Linear parameter varying (LPV) descriptor systems [18,19] can provide good design freedom to achieve desired system robustness, closed-loop stability and performance. The power of this approach stems from the combined use of differential and algebraic equations in descriptor systems and the potential to account for rational system parameter variations when using LPV modelling and feedback for estimation or control. In particular, extended state observer (ESO) of LPV descriptor systems approaches can facilitate the estimation of system states and sensor and actuator faults [20,21].

This paper develops the descriptor system active fault tolerant control (AFTC) scheme within an LPV framework as developed in Ref. [20] with application to the wind turbine benchmark proposed in Ref. [12] which is naturally nonlinear. The remainder of the paper is organized as follows: The system model with the baseline controller in high wind speed region is depicted in Section 2. Since it is common to demand to retain the practically proved baseline controller when a more advance control scheme is employed, an

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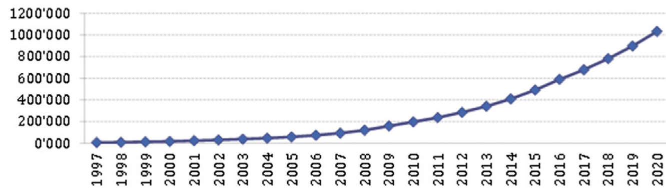

Fig. 1. Total installed capacity of wind turbine during 1997–2020 [MW] [2].

observer based active fault tolerant control system is designed in Section 3. An integrated AFTC scheme is described using an ESO which provides estimates of both system states and faults. Section 4 shows the simulation results for different faults, including sensor faults, and actuator faults. Conclusions are given in Section 5.

2. Wind turbine system description

A typical wind turbine can be depicted as in Fig 2. The goal of this study is to develop an AFTC control scheme of a benchmark wind turbine model described by Ref. [12]. The purpose of the benchmark is to compare and evaluate FDI and fault accommodation designs, as well as FTC schemes with view to selecting the most promising approaches for real wind turbine system applications. The benchmark model is of a three blade horizontal wind turbine which consists of static aerodynamic, drive train, generator, converter and pitch systems. The wind turbine benchmark system has several faults which effectively act in different subsystems.

2.1. Aerodynamics

The aerodynamics of the wind turbine are modelled terms of the aerodynamic torque $T_r(t)$ acting on the rotor blades, represented by:

$$T_r(t) = \sum_{i=1}^{3} \frac{\rho\pi R^3 C_q(\lambda(t), \beta_i(t)) v_\omega^2(t)}{6} \tag{1}$$

where C_q is the torque coefficient table described by Fig 3, $\beta_i(t)$ is the pitch angle for the ith rotor blade, where $i = 1,2,3$. ρ is the air density; R is the radius of the area swept by the blades; $v_\omega(t)$ is the effective wind speed. This model is valid for small differences between the $\beta_i(t)$ values. When $\beta_1(t)$, $\beta_2(t)$ and $\beta_3(t)$ are equal, $T_r(t)$ is then rewritten as:

$$T_r(t) = \frac{1}{2}\rho\pi R^3 C_q(\lambda, \beta) v_\omega^2 = K C_q(\lambda, \beta) v_\omega^2 \tag{2}$$

Another important parameter is the power coefficient table $C_p(\lambda,\beta)$, which has a relationship with $C_q(\lambda,\beta)$ [5] as:

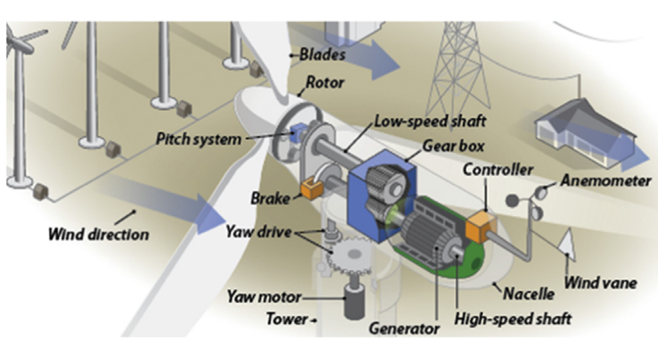

Fig. 2. A typical wind turbine structure [22].

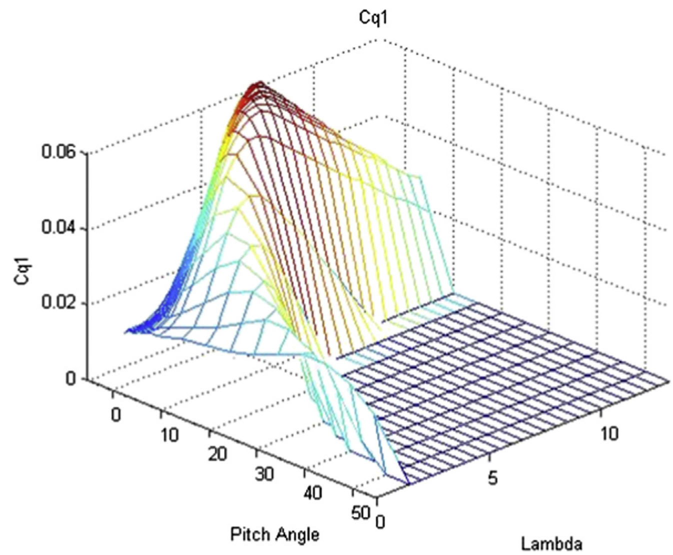

Fig. 3. Rotor aerodynamic torque coefficient table.

$$C_p(\lambda, \beta) = \lambda C_q(\lambda, \beta) \tag{3}$$

2.2. Drive train

The drive train is described as the following linear system.

$$\begin{bmatrix} \dot{\omega}_r(t) \\ \dot{\omega}_g(t) \\ \dot{\theta}_\Delta(t) \end{bmatrix} = \begin{bmatrix} -\frac{B_{dt}+B_r}{J_r} & \frac{B_{dt}}{N_g J_r} & \frac{-K_{dt}}{J_r} \\ \frac{\eta_{dt} B_{dt}}{N_g J_g} & \frac{-\frac{\eta_{dt} B_{dt}}{N_g^2} - B_g}{J_g} & \frac{\eta_{dt} K_{dt}}{N_g J_g} \\ 1 & -\frac{1}{N_g} & 0 \end{bmatrix} \begin{bmatrix} \omega_r(t) \\ \omega_g(t) \\ \theta_\Delta(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{J_r} & 0 \\ 0 & -\frac{1}{J_g} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} T_r(t) \\ T_g(t) \end{bmatrix} \tag{4}$$

where is J_r the moment of inertia of the low speed shaft, K_{dt} is the torsion stiffness of the drive train, B_{dt} is the torsion damping coefficient of the drive train, B_g is the viscous friction of the high speed shaft, N_g is the gear ratio, J_g is the moment of inertia of the high speed shaft, η_{dt} is the efficiency of the drive train, and $\theta_\Delta(t)$ is the torsion angle of the drive train. The potential faults in this subsystem include faults acting in the generator and turbine rotor speeds.

2.3. Generator and convertor systems

The converter dynamics can be modelled by a first order transfer function.

$$\frac{T_g(s)}{T_{g,r}(s)} = \frac{\alpha_{gc}}{s + \alpha_{gc}} \tag{5}$$