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ORIGINAL ARTICLE

Robust fault detection for wind turbines using reference model-based approach

Moazzam Nazir *, **Abdul Qayyum Khan** [1], **Ghulam Mustafa** [1], **Muhammad Abid** [2]

Department of Electrical Engineering, PIEAS, P.O. Nilore, Islamabad, Pakistan

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Abstract This paper presents a reference model-based approach for detection of different faults in a wind turbine. Stochastic uncertainty has been considered in the model of wind turbine. The fault detection scheme is so designed that the generated residual is robust against the uncertainty. For residual evaluation purpose, generalized likelihood ratio (GLR) test has been performed. Threshold is computed using the table of chi-square distribution with one degree of freedom. Occurrence of a fault is concluded whenever evaluated residual crosses the threshold. Using this approach an actuator and a sensor fault in the pitch system and a sensor fault in the drive train system are successfully detected. Results are compared with Combined Observer and Kalman Filter (COK) approach (Chen et al. 2011) used for wind turbine fault detection with this approach requiring less detection time thus providing a more useful solution to the wind industry.

1. Introduction

Wind turbines are used to convert wind energy into electrical energy. Wind energy is clean and renewable. It contributes a lot in the overall world's energy demands. Now a days, wind turbines in megawatt sizes are in operation throughout the world. As sizes of wind turbines increase, reliability becomes an important issue. A lot of work is being done to ensure service reliability and performance (Parsa and Parand, 2012). Reliability can be ensured using efficient fault detection methods. Wind turbine may work well even in the presence of mild faults but severe faults should be detected as quickly as possible so as to prevent the wind turbine from any severe damage.

A three-blade horizontal-axis wind turbine is considered in this paper. Blades of the turbine are facing the wind direction. These blades are connected to the rotor. As wind turns the blades, they cause the rotor shaft or the low-speed shaft to rotate. A gear box is used to upscale the speed to a level at which generator can generate electricity. There are two regions of operation; partial load region and full load region. Power production in partial load region is controlled by converter reference torque control, where as in the full load region, the objective is achieved with the help of pitching the blades of the wind turbine. Feedback mechanism (Elnaggar and Khalil, 2016) that is highly developed is employed for the purpose.

* Corresponding author. Tel.: +92 336 9901101.
E-mail addresses: moazzam.nazir1@gmail.com (M. Nazir), aqkhan@pieas.edu.pk (A.Q. Khan), gm@pieas.edu.pk (G. Mustafa), mabid@pieas.edu.pk (M. Abid).
[1] +92 51 (0) 2207 380 4x3452.
[2] +92 51 (0) 2207 380 4x3440.
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The last three decades witnessed tremendous efforts in the area of fault detection and isolation both in academia and application. For a good insight, the interested reader is referred to Gertler et al. (1998), Blanke (2003), Ding (2008), Isermann (2011), Khan (2011) and Chen and Patton (1999). In the recent past, fault detection and tolerance of the wind turbine has been the focus of attention of researcher community. To this end, several techniques have been proposed. An unknown input observer based design for diagnosing faults in the wind turbine converter has been reported in Odgaard and Stoustrup (2009). A set-membership approach has been proposed in Tabatabaeipour et al. (2012). An observer based scheme for estimating pitch sensor faults is described in Wei et al. (2008) and for gearbox in Sheldon et al. (2014). A scheme based on parity equations for fault detection of wind turbines is presented in Dobrila and Stefansen (2007). A technique using up–down counters for detection of various faults has been presented in Ozdemir et al. (2011). A fault detection system using data-driven technique is designed in Yin et al. (2014). In Svärd et al. (2011), an automated design method of fault detection and isolation of wind turbines is proposed. A data-based approach has been presented in Laouti et al. (2011) in which process knowledge is not required like the other model based approaches.

In this paper, reference model-based approach (Ding, 2008) is exploited for fault detection in wind turbine. Standardized wind turbine model (Odgaard et al., 2009), that is being used by the researchers throughout the world, is used for the analysis. As a result, improvements presented in this research are likely to be adopted by the wind turbine industry. Two subsystems; that is; drive train system and pitch system are considered. Stochastic uncertainty is considered in the parameters of these systems. There are various causes of such model uncertainities including manufacturing tolerances, aging, insect and dirt contamination. Manufacturing tolerances mean that there is always a difference between mathematical model and actual process even when no fault is there. If the model uncertainities are not countered false alarms or missing alarms may occur that will seriously hinder the smooth operation of the wind turbine. The proposed FD scheme is robust against model uncertainty because of the reference model strategy. An optimal reference residual model for wind turbine subsystems is developed and a fault detection filter is then designed with its gain found using a series of LMI's. LMI solution provides efficient and reliable desirable RFDF filter. It is also interesting that there is impulsive change in the residual against some faults in the system. This, in practice, possesses difficulty in detecting such fault. In order to enhance the detectability of these faults, a post filter is proposed. Intuitively, the residual signal should be zero for fault-free case and deviate from zero otherwise. It is interesting to note that, in practice, the generated residual is non-zero even in the absence of fault in the system. Further processing of the residual is, therefore, needed. This stage includes residual evaluation and threshold setting. A systematic design of threshold for FD purpose has also been addressed in the literature, see for instance, Ding (2008), Khan and Ding (2011) and Abid et al. (2009). In this work, GLR has been used for evaluation and threshold design purpose. Threshold is found using the table of chi-square distribution with 1 degree of freedom. Then GLR test is applied that is famous for change detection. In this test, occurrence of a fault is declared whenever evaluated residual crosses the pre-defined threshold.

The rest of the paper is organized as follows: Brief introduction to the wind turbine system and model of different subsystems is given in Section 1. Reference model-based approach has been presented in Section 2. Generalized likelihood ratio test is given in Section 3. Simulation results to show the effectiveness of the proposed approach are shown in Section 4. Finally a conclusion is drawn in Section 5.

2. Mathematical model of wind turbine

A three-blade horizontal-axis wind turbine is considered in this paper. This turbine works on the principle that wind acts on the three blades of the turbine resulting in a motion of the rotor shaft. The rotational speed is upscaled with the help of a gear box to a speed at which generator can generate electricity. Rotational speed is controlled in two ways: converter reference torque control and pitch angle control of the turbine blades. Converter reference torque control is used in the partial load region, whereas, pitch angle control is used in full load region of operation of the wind turbine. Pitch angle is changed using hydraulic actuators which turn the blades according to the requirement. Sensors are used to measure the pitch system position. For the drive train system, rotor and generator speeds are also measured using sensors. In this section models of different subsystems of the wind turbine including pitch system and drive train system have been presented. These models can be found in Odgaard et al. (2009).

2.1. Pitch system model

The pitch system controls the pitch angles of the blades of wind turbine. Sensors are used to measure the blades position. It is a hydraulic system with one hydraulic actuator for each blade. The pitch actuator is modeled with a second order system and its nominal dynamics are described as

$$\frac{\beta(s)}{\beta_{ref}(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{1}$$

where $\beta(t)$ is pitch angle, $\beta_{ref}(t)$ is the reference to the pitch angle, ω_n is the natural frequency of the pitch actuator model, ζ is the damping ratio of the pitch actuator model. This transfer function is discretized for use in the fault detection approach. The discretized state space model is given as

$$x(k+1) = A_p x(k) + B_p u(k) \tag{2}$$

$$y(k) = C_p x(k) + D_p u(k) \tag{3}$$

where

$$A_p = \begin{bmatrix} 0.0247 & -5.536 \\ 0.04485 & 0.6226 \end{bmatrix},$$
$$B_p = \begin{bmatrix} 0.04485 \\ 0.003058 \end{bmatrix}, \quad C_p = [0 \quad 123.4], \quad D_p = [0] \tag{4}$$

2.2. Drive train model

Wind rotates the blades of the wind turbine. Drive train system has gears in it to upscale the rotor speed to a level required by the generator for generation of electricity.