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Fault-tolerant cooperative control in an offshore wind farm using model-free and model-based fault detection and diagnosis approaches ☆

Hamed Badihi [a], Youmin Zhang [a,b,*], Henry Hong [a]

[a] Department of Mechanical and Industrial Engineering, Concordia University, Montreal, Quebec H3G 1M8, Canada
[b] Department of Information and Control Engineering, Xi'an University of Technology, Xi'an, Shaanxi 710048, China[1]

HIGHLIGHTS

- AFTCC schemes using an integrated FDD and FTC approach are developed.
- A model-free FDD system is designed using a rule-based threshold test technique.
- A model-based FDD system is designed using a fuzzy modelling technique.
- Different simulations are performed on a high-fidelity offshore wind farm model.
- Effective fault detection, diagnosis and accommodation results are achieved.

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ABSTRACT

Given the importance of reliability and availability in wind farms, this paper focuses on the development of fault diagnosis and fault-tolerant control schemes in a cooperative framework (referred to as active fault-tolerant cooperative control) at the wind farm level against the decreasing power generation caused by turbine blade erosion and debris build-up on the blades over time. In more details, the paper presents a novel integrated fault detection and diagnosis and fault-tolerant control approach oriented to the design and development of two active fault-tolerant cooperative control schemes for an offshore wind farm. Each of the schemes employs a fault detection and diagnosis system to provide accurate and timely diagnosis information to be used in an appropriate automatic signal correction algorithm for accommodation of faults in the wind farm. The effectiveness and performance of the proposed schemes are evaluated and compared using different simulations on a high-fidelity offshore wind farm benchmark model in the presence of wind turbulences, measurement noises and realistic fault scenarios.

1. Introduction

As one of the most cost-competitive forms of renewable energy, wind has remarkable potential for fulfilling the increasing demand for global energy in an environmentally responsible way. To further reduce the average cost of wind energy, large wind turbines are often installed in clusters called wind farms, particularly at offshore locations. As more and more offshore wind farms are developed further from shores, both the factors of complexity and limited accessibility and harsh climate conditions come into play, resulting in higher failure rates and maintenance challenges. This motivates the design and development of advanced fault detection and diagnosis (FDD) and fault-tolerant control (FTC) schemes in wind farms to improve their reliability and availability.

The FTC schemes can be designed in either passive or active ways. A passive FTC (PFTC) scheme employs the robustness of the closed-loop control system to accommodate faults, while an active FTC (AFTC) scheme reconfigures the closed-loop control system after fault occurrence. AFTC schemes usually require FDD information in the process of control reconfiguration.

In general, the FDD and FTC schemes can be applied at both the individual wind turbine and entire wind farm levels. Recently, research has been more focused on the application of such methods at wind turbine level (for example, see [1–5]). Most of these works try to address the FDD and FTC problems in two standard wind turbine benchmark models presented in [6,7]. A recent

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* Corresponding author at: Department of Mechanical and Industrial Engineering, Concordia University, Montreal, Quebec H3G 1M8, Canada.
E-mail addresses: h_bad@encs.concordia.ca, h.badihi@gmail.com (H. Badihi), Youmin.Zhang@concordia.ca (Y. Zhang), Henry.Hong@concordia.ca (H. Hong).
[1] During his Sabbatical Leave from Concordia University.

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review of the literature in [8] provides more references on FDD and FTC for wind turbines. In reality, some faults are more easily detected, diagnosed, and accommodated at the wind farm level. This can be performed by comparing the performance of turbines operating under similar wind conditions. The FDD and FTC at the wind farm level is a very recent field of research with only a few research works reported in the literature. Most of these works are focused only on condition monitoring and fault detection in wind farms. In [9,10], various data-mining algorithms are applied to develop models for predicting possible faults in wind farms. In [11], the relationship between the wind speed and the generated power in a wind farm is estimated using three different machine learning models. The models can detect anomalous functioning conditions of the wind farm, but they are unable to isolate and identify faults. More recently, researchers have studied the FDD and FTC problems in a standard benchmark model presented in [12] that represents a wind farm with nine turbines that are subject to different fault scenarios. For example, the authors in [13] present a fault detection and isolation approach based on a set of piecewise affine Takagi-Sugeno models that are identified from noise-corrupted measurements. Borcehrsen et al. [14] present a fault detection system relying on dynamical cumulative sum for residual evaluation, and a load distributing controller for accommodating possible faults. A passive FTC scheme is presented in [15] that integrates a fault estimation scheme with the design of a controller accommodation system. An evaluation study is also presented in [16]. Duviella et al. [17] propose an evolving classification algorithm for detection and isolation of faults due to debris build-up on the wind turbine blades. In [18], the fault diagnosis is conducted using interval nonlinear parameter-varying parity equations, assuming an unknown but bounded description of the noise and modelling errors. Another work reported in [19] presents an active fault-tolerant control scheme based on a model-based FDD approach. In actuality, the above cited research works are similar in two aspects: first, they have assumed that only one fault occurs at a time in a farm, and second, they mostly rely on wind speed or its estimation which normally depends on the layout of the wind farm and direction of the wind as well. For example, the algorithms proposed in [14,17,18] are only developed for one or two specific wind directions.

Given the importance of FDD and FTC at a wind farm level, this paper presents a novel integrated FDD and FTC approach in a cooperative framework referred as the active fault-tolerant cooperative control (AFTCC) by recognizing the differences in controlling a wind farm from a single wind turbine. Here, the term "active" is due to the integrated design of both FDD and FTC [20], while the term "cooperative" is due to the cooperative design for multiple wind turbines (wind farm) which is beyond a design for a single wind turbine and will be demonstrated in the later parts of this paper for both FDD and FTC strategies. The proposed approach is oriented to the design and development of two AFTCC schemes for an offshore wind farm against decreased power generation faults that is caused by turbine blade erosion and debris build-up on the blades over time. The first scheme is based on a model-free FDD system that incorporates a rule-based threshold testing technique for residual evaluation. Conversely, the second scheme is based on a model-based FDD system that incorporates data-driven models developed using a fuzzy modelling and identification (FMI) technique. Both schemes are relying on an appropriate automatic signal correction (ASC) algorithm that employs the provided accurate and timely FDD information for accommodating the possible faults in a wind farm.

The proposed AFTCC schemes not only provide necessary FDD information for condition monitoring purposes, but also provide the effective possibility of the accommodation of faults in a wind farm. To further highlight the contribution of this paper compared to the other relevant works in the existing literature, it is worth mentioning that the proposed schemes in this paper are designed and developed in a way to be valid for any layout of a wind farm with any direction of the wind, while the considered fault may occur simultaneously in more than one turbine in the farm. This is actually a more general case that may happen in a real wind farm in operation, and has never been studied in the available literature so far.

The effectiveness and performance of the proposed AFTCC schemes are evaluated and compared using different simulations on a high-fidelity offshore wind farm benchmark model in the presence of wind turbulences, measurement noises and realistic fault scenarios. Moreover, extensive Monte Carlo simulations are performed to evaluate the robustness of the proposed schemes with respect to modelling errors, disturbances and measurement uncertainties.

The remainder of the paper is organized as follows: In Section 2, the wind farm benchmark model used in this paper is briefly described. The considered fault is described and analysed in Section 3. Section 4 presents the AFTCC based on integrated FDD and FTC approach against the fault discussed in Section 3. The details of the FDD at wind farm level are presented in Section 5. Section 6 presents the simulation results with some comments and discussions. Finally, conclusions are drawn in Section 7.

2. Overview of the wind farm benchmark model

This paper considers an advanced wind farm simulation toolbox called *SimWindFarm* that is developed as a part of the EU-FP7 project, AEOLUS [21]. The toolbox provides a realistic wind farm simulation benchmark model that allows control designers to

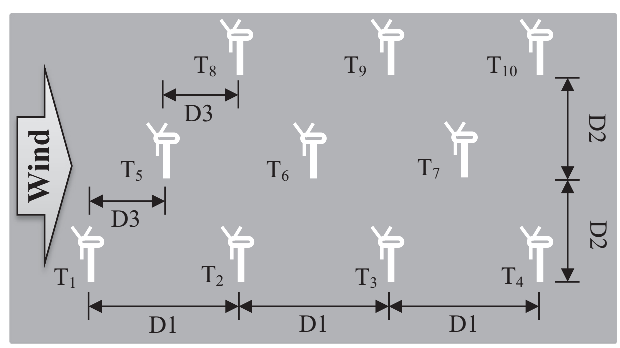

Fig. 1. Wind farm layout (D1 = 600 m, D2 = 500 m, D3 = 300 m).

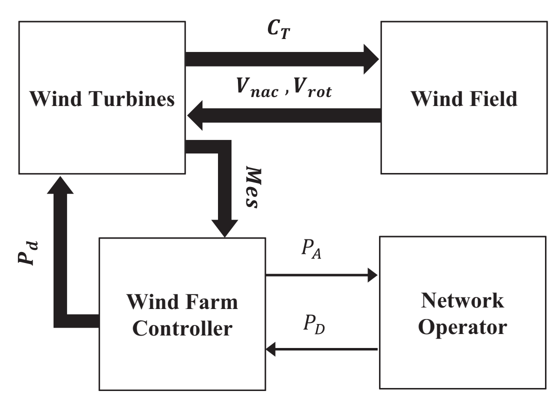

Fig. 2. Illustration of overall model structure for N turbines. Note that the bold letters stand for sets of variables, for example $\boldsymbol{P_d} = [P_{d,q}]$ with $q = 1, 2, \ldots, N$ (This figure is based on [21]).

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