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Power extraction efficiency optimization of horizontal-axis wind turbines through optimizing control parameters of yaw control systems using an intelligent method

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HIGHLIGHTS

- Two favorable yaw control systems are developed and optimized.
- Intelligent optimization method is proposed to optimize the potential performance.
- Power extraction efficiency is optimized by 0.32% and 0.8% for two control systems.
- Optimized efficiency under small wind variation is 1.5% more than the large variation one.
- Novel yaw control strategy employing optimized parameters is suggested.

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ABSTRACT

To optimize the power extraction from the wind, horizontal-axis wind turbines are normally manipulated by the yaw control system to track the wind direction. How is the potential power extraction efficiency of such wind turbines related to the parameter optimization of a yaw control system? We intend to answer this question in this study. First, we develop two control systems, a direct measurement-based conventional logic control (Control system 1), and a soft measurement-based advanced model predictive control (Control system 2). Then, a multi-objective Particle Swarm Optimization-based method is introduced to optimize control parameters and search for the Pareto Front, which represents different potential performance. On this basis, result investigation and analysis are carried out on an electrical yaw system of China Ming Yang 1.5 MW wind turbines based on three wind directions with different variations. Experimental results show that, under a large wind direction variation and with a 14% yaw actuator usage, 0.32% and 0.8% more power extraction efficiency are gained by Control system 1 and 2, respectively, after optimization. The achievable power extraction efficiency for the two yaw control systems goes down when the allowable yaw actuator usage is reduced. For instance, when the yaw actuator usage is 14%, 4.9% and 2%, the efficiency is 97.19%, 96.76% and 96.37% for Control system 1, and is 97.73%, 96.76% and 95.45% for Control system 2, respectively. Therefore, Control system 2 takes precedence over Control system 1 for having higher efficiency when the allowable yaw actuator usage is more than 4.9%. We also find that the potential power extraction efficiency of the two control systems is significantly influenced by the wind direction variation, that is, the optimized efficiency under small wind direction variation is 1.5% higher than that under large wind direction variation. In addition, the parameters of Control system 1 need to be re-optimized according to the wind condition, whereas the ones of Control system 2 may not. Finally, a novel yaw control strategy employing the optimized parameters as the query tables is suggested for the real applications.

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1. Introduction

To compete with other types of energy resources, the focus of research today in wind energy field lies in maximizing the power production of wind turbines (WTs) per unit investment. Accordingly, maximum power extraction efficiency (PEE) has been regarded as the primary objective of controlling WTs [1–3]. For a horizontal-axis WT, the maximum PEE is referred to as two aspects [4]: maximizing aerodynamic power coefficient, which is fulfilled through controlling the rotor speed and the pitch angle of WTs according to the wind speed, and minimizing the yaw error, which is achieved through adjusting the nacelle position of WTs to track the wind direction.

In the literature, great research interest has been drawn into the first aspect of maximum PEE, where effective wind speed estimation-based algorithms have been proven effective in providing high efficiency power production [5–7]. By comparison, quite limited efforts have been made towards minimizing the yaw error, which is in the charge of the yaw control system (YCS). The objective of the YCS is to minimize the yaw error with an acceptable yaw actuator usage. Nevertheless, the minimization of yaw error may induce the over usage of the yaw system, because it requires a continuous action of yaw actuator. For industrial WTs, the PEE performance achieved by the YCS is not fulfilled in a satisfactory manner. A study of operating WTs has revealed that the static yaw error is about 10 degree and 5 degree for wind speeds below and above 20 m/s, respectively [8]. In a typical case of Horns Reef wind farm, the potential power loss due to the yaw error is 2.7% [9]. Besides, the over usage of the yaw actuator has frequently occurred in the wind energy industry. The survey of wind power system failures reveals that the yaw failure rate is approximate 12.5% of the whole one [10]. From these results, it is concluded that the YCS should deserve more attention than it received.

Some control methods have been proposed for the YCS, and they directly rely on the measurement devices. Limited by the wind measurement technology, early WTs use the hill climbing control method to activate the yaw system [11,12]. As the development of wind direction sensors, modern WTs employ active yaw control strategies, which are comparably simple and use some predefined logic controls [13–16]. Although the control logic is simple, the difficulty consists in obtaining a precise and real-time control reference from the wind direction measurements which are noticeably disturbed by operation of the WTs [17]. To handle this issue, an averaging filter is widely utilized by the YCS of industrial WTs, but it results in a time delay for the control use. On the other hand, it is hard for the slowly moving nacelle position to track the quickly changing wind direction. Thus, the conventional yaw control methods based on the direct wind direction measurements could not provide sufficient performance. Recently, there has been a growing interest in how the YCS can be further improved using advanced measurement devices [18,19], but the measurement device is very expensive. The cost-effective alternative is the soft measurement-based method, which uses the short-term prediction of wind direction. Despite many efforts made towards forecasting approaches relevant to the wind source [20–25], none of them tried to employ the predicted wind data into the control application of WTs. Motivated by above observations, we have proposed a novel yaw control solution using predicted wind directions for maximum PEE of WTs in [26], the structure of which consists of a wind predictive model and a novel model predictive control (MPC) strategy. By comparison to the industrial solution, the proposed one is capable of further reducing yaw error with a modest yaw actuator usage, but the ultimate potential of the PEE as a result of parameter optimization is not quantified and evaluated in the previous study. Indeed, establishing the performance limitations of different control methods through parameter optimization will provide insight to the control method that potentially will offer greater benefit to WTs. In addition, investigating the potential performance of different YCSs can help designers and customers of WTs to select the most suitable YCS according to their needs.

The objective of the present study is to fill the aforementioned knowledge gap and to find the suitable YCS that provides the best achievable performance of the PEE with an acceptable yaw actuator usage. To do this, the conventional control method using the direct wind direction measurement and the advanced MPC method using the predicted wind directions are investigated. Specifically, this study evaluates the control strategy which is detailed in [13–15] and employed by the NREL CART3 (Controls Advanced Research Turbine 3-Bladed) turbine, and the control strategy proposed in [26], both of which use several predefined parameters. Therefore, it is important to carry out an investigation on the potential performance of the two control methods on the basis of parameter optimization. To do this, two YCSs based on these two yaw control methods are developed and optimized to simultaneously achieve two explicit objectives, namely, minimization of power reduction factor caused by the yaw error and minimization of yaw actuator usage during wind direction tracking. In order to address the two-objective issue and the constraints in the automated optimization process, multi-objective optimization method needs to be employed.

Currently, multi-objective optimizations based on Pareto optimal theories have been intensively studied, and some intelligent algorithms have been applied for the WT design. Using multi-objective optimization algorithms, the designers of WTs are able to identify a trade-off curve called Pareto Front that reveals the weakness, anomalies and rewards of certain targets [27]. For a stall regulated horizontal-axis WT design, a genetic diversity evaluation method is introduced to achieve the best trade-off performance between two objectives: maximization of annual energy production per square meter of wind farm, and minimization of cost of energy [28]. For a blade geometry optimization of WT rotors which considers aerodynamics, structures, noise, and cost, an existing computer program named PROPGA based on a genetic-algorithm (GA) is used in [29]. For a WT blade design with the objectives of power coefficient and noise levels under uncertainty, the GA optimization strategy is also used in [30]. For a WT blade design with the objectives of maximum of annual energy production and minimum of blade loads, and for a 5 MW WT blade design taking the maximum power coefficient and the minimum blade mass as the optimization objectives, the non-dominated sorting genetic (NSGA)-II algorithm is employed in [31] and [32], respectively. Recently, the same authors of [32] propose a gradient-based multi-objective evolution algorithm based on uniform decomposition and differential evolution for a 1.5 MW WT blade design [33].

Besides aforementioned intelligent optimization algorithms, Particle swarm optimization (PSO) is recognized as another simple concept algorithm, with easy coding implementation, robustness to control parameters and computational efficiency [34], and it has been proposed to minimize the blade mass of a 1.5 MW WT [35]. Since the PSO strategy was firstly extended for solving multi-objective problems in [36], multi-objective particle swarm optimization (MOPSO) has been widely used in solving multiple-objective optimization problems of renewable energy systems [37,38]. In this work, the MOPSO algorithm is proposed to solve the aforesaid two-objective issue through optimizing the control parameters of two YCSs. On this basis, the potential performance of the PEE provided by the two YCSs is optimized and evaluated, which corresponds to the yaw actuator usage and the control parameters.

The novel contributions of this study can be summarized as follows:

- This is the first study that addresses the achievable performance of the PEE for WTs through optimizing YCS. To our best of knowledge, only a few works have been carried out to propose new control solutions for the YCS of WTs, and none of them evaluates the potential performance of the PEE, which is surely affected by both the yaw actuator usage and the control parameters of the YCS.
- This study investigates the effects of wind direction condition on the potential performance of the YCS for the first time. Because the YCS