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# Comparative studies on control systems for a two-blade variable-speed wind turbine with a speed exclusion zone

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ABSTRACT

To avoid the coincidence between the tower nature frequency and rotational excitation frequency, a SEZ (speed exclusion zone) must be built for a two-blade wind turbine with a full rated converter. According to the literature, two methods of SEZ-crossing could be adopted. However, none of them have been studied in industrial applications, and their performance remains unclear. Moreover, strategies on power regulation operation are not covered. To fully investigate them, this paper develops two control systems for a two-blade WT (wind turbines) with a SEZ. Because control systems play vital roles in determining the performance of the WT, this paper focuses on comparative studies on their operation strategies and performance. In these strategies, optimal designs are introduced to improve existing SEZ algorithms. Moreover, to perform power regulation outside the SEZ, two operation modes are divided in the proposed down power regulation solutions. The developed control systems' performance is confirmed by simulations and field tests. Two control systems present similar capabilities of power production and SEZ-bridging. Nevertheless, at the cost of significantly increased tower loads, one captures 1% more energy than the other. Overall consideration must be made for the control system selection for a WT with a SEZ.

## 1. Introduction

A wind turbine system is a system that converts mechanical energy obtained from wind into electrical energy through a generator. It can be categorized by types of generators used, power control methods, constant- or variable-speed operations, and methods of interconnection with the grid [1]. To ensure high performance while minimizing costs, new solutions are developed constantly for WT (wind turbines) (). Fundamental changes have been addressed, such as continuously variable transmissions [2,3] and new sensing technologies [4,5]. Meanwhile, advanced control algorithms have been widely studied, such as soft computing techniques [6,7] and sustainable control [8]. Despite the development of good concepts in recent years, engineering and science challenges still exist.

Modern high power WTs are typically designed in a variable-speed type, capturing wind energy and reducing the mechanic loads effectively. However, a wide speed operation region allows the resonance between rotor rotary frequency and natural frequencies of other structural components. To tackle underlying problems, some methodologies are applied during the design phase, including natural characteristic calculations and potential resonance analyses [9]. Considerations include not only the certain gap reserved among the natural frequencies of the blades, tower and driver train but also the avoidance of coincidences among natural frequencies and external resonance force [10]. It is recommended that the eigen-frequency of the rotor blade be outside a 12% range of the rotational frequency of the WT and the lowest mode frequency of the tower be kept outside ranges defined as ±10% of the rotor frequency and ±10% of the blade passing frequency [11]. In practical applications, the tower resonance is dangerous because it results in the vibration of the whole WT set. For a three-blade WT, it is possible to move the natural frequency to the region between 1 P and 3 P by redesigning the tower's thickness and radius. However, this approach does not work for a two-blade WT because changing the tower's natural frequency to be lower than 1 P or higher than 2 P will greatly increase the cost. Therefore, to prevent the WT from operating in the SEZ (speed

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**Nomenclature**

| | |
|---|---|
| $\theta_{set}$,$\theta_m$ | the pitch angle set-point and the measured pitch angle. |
| $w_A$,$w_B$,$w_C$, $w_D$ | four speed points at optimal tip speed section. |
| $w_b$,$w_c$ | the lower and upper speed boundaries of the speed exclusion zone. |
| $w_o$ | the critical speed of a two-blade wind turbine. |
| $w_{r\_p}$ | the speed reference of the pitch controller |
| $w_{r\_pl}$, $w_{r\_ph}$ | $w_{r\_p}$ in low power mode and high power mode |
| $w_{r\_t}$ | the speed reference of the PI torque controller |
| $w_{r\_tl}$,$w_{r\_th}$ | $w_{r\_t}$ in low power mode and high power mode |
| $w_{r\_m}$ | the measured rotor speed |
| $T_{opt}$ | the optimal generator torque |
| $P_{set}$ | the power command from wind farm controller |
| $P_{rated}$, $P_m$ | the rated power and the measured electrical power |
| $P_{set\_b}$ | the power set-point to the boost converter controller |
| $P_l$ | the power set-point from the lookup torque controller |
| $P_{l\_l}$, $P_{l\_h}$ | $P_l$ in low power mode and high power mode |
| $P_B$, $P_C$ | the power set-points at rotor speeds $w_B$ and $w_C$ |
| $P_E$, $P_F$ | the upper and lower power limits at the speed boundaries $w_b$ and $w_c$ |
| $P_{l1}$, $P_{l2}$, $P_{l3}$ | three power limits at the speed boundary $w_c$ |
| $P_{h1}$, $P_{h2}$, $P_{h3}$ | three power limits at the speed boundary $w_b$ |
| $t_{task}$,$t_{cross}$ | time of control system task and set time to cross the SEZ |
| $H_s$, $H_m$,$H_l$ | three hysteresis time |
| Mx, My, Mz | the rolling, nodding and yawing moments |

exclusion zone), the only feasible way is to redesign the control system.

Control algorithms for a WT with a SEZ are described in previous works [12–17]. Among these works, two control approaches can be distinguished. The first one, recorded in [12], is based on the torque control with a conventional lookup table. The second one, proposed in [13–15], is developed based on a proportional integral (PI) torque control method. In both of them, a certain speed region, including the critical speed and its vicinity, is built up to form the SEZ. Differences between them are the means of establishing and bridging over the SEZ. The first approach is to create an ambiguous function between rotor speed and generator torque, so that the generator can accelerate to cross the SEZ, through an unbalanced relation between the aerodynamic torque and demanded generator torque. The second is to gradually adjust the speed reference from one fixed speed boundary to another. Despite the two approaches available, studies about their applications in real wind turbines are few. As far as we know, only in [16] are different widths of SEZs, based on the second approach, investigated and validated on a 1.3 kW test rig. In addition, in [17], the first approach is employed for the design of a two-bladed WT's control system. In the wind energy industry, control strategy validation through field trials is vital and irreplaceable. Based on field trials and related data analysis, for the control approach applied in [17], two drawbacks are exposed: i) the experimental turbine fails to cross over the SEZ under certain wind conditions; ii) the power capture performance is unsatisfactory. Therefore, optimization techniques must be further investigated. Moreover, the performance of available control approaches is not studied in the literature, which is vital for WT designers and owners to select a control system for a WT with a SEZ.

The control strategies discussed above are utilized only to maximize power production while maintaining the desired rotor speed and avoiding equipment overloads [18]. Currently, wind farms are required to play roles similar to those of conventional power plants in power systems [19]. As a result, WTs are commanded to regulate power according to the power set-points set by central control systems of wind farms. Thus, these WTs must perform three power generation tasks: power optimization, power limitation, and power regulation. These three tasks are fulfilled in a certain operation region, constrained by the rotor speed. In the case of a WT without a SEZ, it is necessary only to limit the rotor speed to the speed reference by the pitch controller under the power limitation. To date, many studies have focused on generic WTs, especially those with doubly fed induction generators [20–24]. For a WT with a SEZ, specific control strategies must be studied, which are required to perform power generation tasks while maintaining the rotor speed outside the SEZ. However, there is no literature on such strategies.

The objective of this work is to perform comparative studies of control systems for a two-bladed WT with a SEZ. Starting from available methods, this paper develops two control systems to perform power generation tasks while bypassing the SEZ. For both of them, three operation strategies are discussed, including power optimization, power limitation and power regulation. In such strategies, optimal designs are introduced to improve existing SEZ algorithms and solve their problems. Moreover, to perform power regulation outside SEZ, simple yet effective down power regulation solutions are presented. The control strategies are verified through simulations and field tests. Their performance is evaluated according to International Electro-technical Commission (IEC) standards.

## 2. Studied two-blade WT

### 2.1. Basic information

The studied WT is a two-blade 3.0 MW super compact drive machine. It is manufactured by China Ming Yang Wind Power Company, and its specifications are shown in Table 1.

The WT has a super compact structure, and its main body consists of two parts: the energy conversion system and its supporting tubular steel tower. The energy conversion system diagram is shown in Fig. 1, including a blade rotor, a low-ratio gearbox, a

**Table 1**
Specifications of the studied WT.

| Parameters | Value |
|---|---|
| Rotor diameter | 110 m |
| Number of rotor blades | 2 |
| Rated electrical power | 3000 kW |
| Rotor speed range | 6.0–21.0 rpm |
| Nominal rotor speed | 16.2 rpm |
| Rated wind speed | 12.2 m/s |
| Rotor moment of inertia | $1.5 \times 10^7 kg \cdot m^2$ |
| Generator moment of inertia | $2.1 \times 10^3 kg \cdot m^2$ |
| Gearbox ratio | 23.94 |
| Cut-in wind speed | 3 m/s |
| Cut-out wind speed | 20 m/s |