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# Classification of operating conditions of wind turbines for a class-wise condition monitoring strategy

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ABSTRACT

Relevant classification of the stationary operating conditions of wind turbines (WTs) aids in the selection of an optimal condition monitoring technique. This paper presents a general method that can be used to classify the operating conditions of WTs in terms of rotor speed and power. In this study, the ideal probability density functions (PDFs) of rotor speed and power are calculated using an analytic WT model and a wind speed profile. To estimate the PDFs of rotor speed and power with field data, two methods are employed: (1) empirical PDF-based and (2) Gaussian mixture model (GMM)-based. The individual PDFs estimated by the two methods are used to quantitatively define the range of the stationary WT operating conditions. The proposed methods and the range of stationary operating conditions established by the methods were evaluated using data from an analytical WT model and an actual 2.5 megawatt WT in the field. In addition, the paper presents the evaluation of the performance of the proposed class-wise condition monitoring strategy when used with vibration signals acquired from a two kilowatt WT testbed. In summary, the proposed strategy and methods are promising for effective condition monitoring of WTs.



## 1. Introduction

Wind turbines (WTs) often suffer from high maintenance costs and downtime due to undesired failures. Condition-based maintenance can effectively prevent many of these undesired failures and thereby reduce the maintenance costs of WTs [1–3]. However, it is often challenging to evaluate the conditions of WTs using readily-available signal processing techniques (e.g., fast Fourier transform) since condition monitoring signals (e.g., vibration) are inhomogeneous and non-stationary [4]. Due to the uncertain nature of wind profiles, highly variable operating conditions are prevalent during the operation of WTs. Several attempts have been made to use the currently available signal processing techniques for robust condition monitoring of WTs by adaptively using homogeneous condition monitoring signals across a limited range of WT operating conditions. For example, the International Electrotechnical Commission (IEC), an organization that proposes international standards for WT condition monitoring, has recommended that "active power bins" should be used to classify the range of power so that the vibration signals in a particular bin are more homogeneous and exhibit only small variations [5]. Thus, it would be expected that a condition monitoring technique could be effectively used with each bin due to the homogeneous nature of the vibration signals in that "bin." However, it is well known that vibration characteristics are also dependent on rotational speed [6,7]. Therefore, the IEC's recommendation of using "active power bins" is not appropriate when rotational speed fluctuates. Another organization, DNV GL, proposed a renewables certification that divides the operating conditions of WTs into two parts based on the amount of variation of the WT's speed [8]. In this strategy, computationally efficient signal processing techniques (such as fast Fourier transform) are used only when WTs operate with minimal speed variation. When the WTs operate with frequent speed variation, it is recommended that more advanced condition monitoring techniques be employed [8].

To effectively monitor WTs, some commercial condition monitoring systems also try to use the existing signal processing techniques only when the WTs are operating in a pre-defined narrow range of operating conditions [9]. For example, "Windcon," developed by SKF, uses the concept of an "active range." This strategy performs active condition monitoring only while rotor speed and

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power remain in the “active range” [10]. The “Oneprod Wind System,” developed by Oneprod, uses wind speed as an additional variable for defining the “active” range for WT monitoring [11]. Although a variety of condition monitoring strategies like these have been proposed that attempt to fully utilize currently available signal processing techniques, it should be noted that to do this, the criteria for the operating conditions of interest for a WT (e.g., the criteria for the “active range” of the “WindCon” method) must be pre-defined by the users. Thus, implementation of the guidelines and options specified by IEC [5], DNV GL [8], SKF [10] and Oneprod [11] is not feasible unless the quantitative criteria for the operating conditions of WTs are given. To the best of our knowledge, there is no practical guideline that quantitatively classifies WT operating conditions to provide an effective range for an optimal WT condition monitoring strategy.

In response to this need, this paper proposes a general method for classification of the operating conditions of WTs in terms of rotor speed and power. The ultimate goal is to use these classifications to establish an optimal strategy for condition monitoring of WTs. Section 2 introduces an analytical WT model that calculates the relationship between input wind speed and power or rotor speed based on a generic control logic for variable-speed WTs. In Section 3, the probability density functions (PDFs) of power and rotor speed are mathematically derived from the analytical WT model to provide a theoretical rationale for the classification method and the criteria for the operating conditions. In Section 4, five distinct classes are developed in such a way that WTs in a particular class have unique operating characteristics, thus leading to homogeneous condition monitoring signals in each class. In particular, to produce the most valuable vibration signal for condition monitoring of WTs, quantitative criteria for the stationary operating condition of WTs are defined, while considering inherent randomness in the performance of WTs. Section 5 presents two case studies: (1) a WT model with various levels of average wind speed and (2) an actual 2.5 megawatt WT in the field. Section 6 discusses the applicability of the proposed classification-based condition monitoring strategy to the industry and presents condition monitoring results for a two kilowatt WT testbed under various operating conditions. This paper concludes with a summary and suggestions for future work, outlined in Section 7.

## 2. Analytical modeling of WT performance

Different control logic strategies are implemented to achieve optimal performance in variable-speed WTs [12]. As illustrated in Fig. 1, in Region 1, the wind speed is less than the “cut-in” wind speed ($v_{cut\text{-}in}$). In this region, the wind energy is considered to be insufficient to produce power. Consequently, the WT is directed not to generate power, and instead stays in an idle mode. When the wind speed exceeds the cut-in wind speed, the rotor starts to rotate at the cut-in rotor speed ($w_{cut\text{-}in}$). In Region 2, the output power of the WT can be characterized as being proportional to the cube of the wind speed [13]. The rotor speed is controlled to maximize the efficiency of the WT's energy production in such a way that the rotor speed can be approximated as being linearly proportional to the wind speed [14]. When the wind speed becomes high enough to generate the rated power ($P_{rated}$) and the rated rotor speed ($w_{rated}$) of the WT, the blade pitch is controlled to maintain the power and rotor speed at constant levels (Region 3). Based on the WT control logic outlined here, the relationship between the wind speed ($v$) and normalized power ($P$), or normalized rotor speed ($w$), can be represented as:

$$P = \begin{cases} 0 & v < v_{cut-in} \\ (v/v_{rated})^3 & v_{cut-in} \le v < v_{rated} \\ 1 & v_{rated} \le v \end{cases} \tag{1}$$

$$w = \begin{cases} 0 & v < v_{cut-in} \\ v/v_{rated} & v_{cut-in} \le v < v_{rated} \\ 1 & v_{rated} \le v \end{cases} \tag{2}$$

On the other hand, it has been reported that any engineered system including WTs has considerable uncertainties due to several issues, such as randomness in geometry, material property and loading (e.g., stochastic nature of the wind property) [15,16]. Based on the work of Tondan and Zhigang, power and rotor speed with random noise can be defined by incorporating Gaussian noise as [17]:

$$P_n = P + \varepsilon_P \tag{3}$$

$$w_n = w + \varepsilon_w \tag{4}$$

where $\varepsilon_p$ and $\varepsilon_w$ represent the Gaussian noise with a mean of zero and a standard deviation of $\sigma$ (i.e., $\varepsilon_p \sim N(0, \sigma_P^2)$, and $\varepsilon_w \sim N(0, \sigma_w^2)$).

To calculate the power and rotor speed using the WT model, wind speed ($v$) must be known. Prior research recommends that wind distribution should be assumed to follow a Rayleigh distribution whose CDF ($F_v$) and PDF ($f_v$) can be defined as [18,19]:

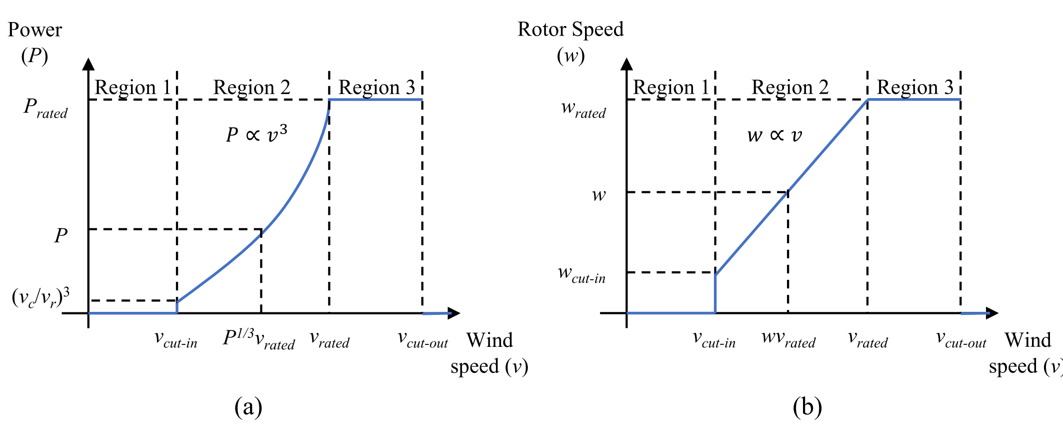


**Fig. 1.** Region of wind speed for control of WTs. (a) wind speed-power relationship. (b) wind speed-rotor speed relationship.

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