Electrical Power and Energy Systems 103 (2018) 497–510

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

A probabilistic assessment approach for wind turbine-site matching

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ARTICLE INFO

Keywords:
Wind turbine performance
Probabilistic performance assessment
Random wind conditions
Wind turbine-site matching

ABSTRACT

This article provides a new methodology for wind turbine-site matching by using a probabilistic approach. The random behavior of the wind speed climate and the uncertainties of wind turbine characteristics are important to take into account in models used to evaluate the performance of the wind turbine. The proposed formulation of the wind turbine-site matching is derived based on the probabilistic reliability assessment approach. It was experimented using different power curve approximation models, for different random conditions, using time series of wind speed in two sites in Morocco: Dakhla and Essaouira. A comparison based on methods used in literature for the estimation of two-parameter of the Weibull function to fit the wind speed distribution is also carried out. The results revealed that the introduced performance indicators are less sensitive to the models used to approximate the wind power curves compared to the deterministic conventional indicator that leads to different rankings and problems of over-sizing or under-sizing. However, those performance indicators are more sensitive to the variation of the wind speed distribution parameter's and can help on accurately estimate the wind power. Moreover, the proposed formulation allows a global sensitivity analysis using Sobol's indices to observe the influence of each input parameter on the observed variances of the performance of a wind turbine. A numerical application illustrates the interpretation of sensitivity indices and shows the impact of the wind speed and the rated wind speed on the variance of the wind turbine performance. This method can help wind energy developers and manufacturers to optimally select WTGs for their future project and accurately forecast the performance of their WTGs for monitoring and maintenance scheduling under uncertainty.

1. Introduction

Due to the effects of fossil fuel energy on the environment, developers have been obliged to seek out other cleaner energy arising from the sustainable resources. Wind energy is perceived as the most affordable, mainly due to its generated electricity capacity and competitive cost [1]. However, the intermittent and the stochastic nature of the wind speed remain the most challenging aspect against the massive integration of this technology. In fact, the characteristics of the wind speed vary with time and space, and the optimal selection of a wind turbine should be conducted carefully in order to find the best Wind Turbine Generator (*WTG*) characteristics with respect to the wind speed availability. It is a critical step from the reliability and cost-benefit point of view. In literature, many studies have been reported on the optimal site matching of wind turbines. Most of these studies are based on Capacity Factor (*CF*)[1], Cost of Energy (*COE*), Annual Net Profit (*ANP*) [2], the Wind Turbine-Site Matching Index (*TSMI*)[3], Turbine cost Index and Integrated Matching Index (*TIIMI*) [4], Normalized Turbine Performance Index (*NTPI*) [5], Amount Of Annual Energy Production (*AEP*) and Wind Turbine Performance Index (*TPI*). Lee et al. [2] assessed the effects of local wind speed and wind turbine power characteristics on the optimum hub height, they concluded that the optimum hub height decreased as the mean wind speed and wind shear exponent increased. Moreover, it was shown that rated power and cut-in speed had little effect, where as rated speed and cut-out speed had much greater effects on optimum hub height. Chang et al. [5] demonstrated that the wind turbine performance would be better if the wind speed Weibull distribution concentrates at higher speed range or especially if it is greater than the wind turbine's rated speed. *WTG* installed at high height could produce more than at lower height because of high rated wind speed occurrence. This may decrease the net annual profit by increasing the initial capital cost of installation and the operation and maintenance cost which may results due to failure caused by excessive wind speed [2]. Chang et al. [5], highlighted that if the wind turbine is selected with low rated speed, it would operate with a high capacity, in this case too much energy would be lost in high wind

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https://doi.org/10.1016/j.ijepes.2018.06.018
Received 22 November 2017; Received in revised form 16 April 2018; Accepted 5 June 2018

Nomenclature

α	Hellman's wind shear component
β_{HL}	The Euclidean distance from P* to the origin of the standard space
$\chi 2$	Chi-square test statistic
γ_f	Indicator function
μ	Average value
∇	The gradient operator
$\Phi(.)$	The standard Gaussian cumulative distribution function
$\phi_n(U)$	n-dimensional standard Gaussian probability distribution function
σ	Standart deviation
c	Scale parameter
CF	Capacity factor
$f(v)$	Weibull probability density function
$f_X(X)$	Joint density function of random variables X
$g(v)$	Non-linear part of power curve
$G(X)$	Performance function
H	Wind turbine hub height
$H(U)$	The performance function expressed in the standard space
h_{ref}	Reference height above ground level
k	Shape parameter
P^*	The most probable failure point in the standard space
P_c	Critical wind power
$P_{elec}(v)$	Electric power of wind turbine
p_{fc}	Probability of full charge operating
p_f	Probability of failure
p_o	Probability of operating
p_{pc}	Probability of partial charge operating
P_r	Rated power
$Pr(.)$	Probability operator
S_i	The first order Sobol indice measuring the variance contribution of variable x_i to the variance of the response
S_{Ti}	The total order Sobol indice measuring the interaction contributions of x_i with all the other variables
U	Vector of standard Gaussian random variables $(u_1, u_2, ..., u_n)$ mutually independent and uncorrelated
$U*$	The coordinate vector of P*
v	Wind speed
$V(h)$	Wind speed at the height h
V_c	Cut-in speed
V_f	Cut-out speed
V_m	Mean wind speed
V_{ref}	Measured wind speed at h_{ref}
V_r	Rated speed
X	Vector of stochastic variables $(x_1, x_2, ..., x_n)$
z_0	Surface roughness length

speed in this site. Contrariwise, if the wind turbine is selected with high rated speed, the wind turbine may extract most of the wind energy, but its capacity becomes low.

In the aforementioned researches, the uncertain aspect of different variables such as *WTG* characteristics or wind shear component was not considered. It was observed and mentioned in [6,7] that the expected typical power curve is often not ideally followed. This could be derived by errors in wind speed measurement, the lack of knowledge of the long term variation of the characteristics of *WTG*, the lack of accuracy in power loss expectation for non-nominal wind conditions as the power curves should be carefully calibrated to the wind conditions in the desired area according to the standard IEC 61400-12 [8].

Few scientific studies were based on a probability or reliability theory. Jung et al. [9] proposed a Bayesian approach to account for uncertainty in wind speed, air density, surface roughness exponent and power performance of the turbine using the Annual Energy Production (*AEP*). Melchers [10] developed an interesting method to evaluate the system performance in using the reliability theory. He proposed the estimation of the failure probability of a system in taking into account the uncertainties influence of input variables (operating conditions) on physical models. He used several methods (First or Second Order Reliability Methods (FORM, SORM), Monte Carlo) for the assessment of the failure probability. Charki et al. [11,12] and Titikpina et al. [13] used the structural reliability approach for studying the performance of other energy systems and mechanical components. They showed that the method proposed by Melchers [10] is suitable for assessing the performance and the reliability of a system.

This paper proposes the adaptation of the method of structural reliability in wind energy. It provides a new methodology for wind turbine-site matching issue taking into account the uncertainties derived from the random behavior of wind speed climate and uncertainties likewise concern *WTG* characteristics and models used to approximate the *WTG* power curve. Various methods (Maximum Likelihood Method (*MLM*), Least Squares Estimation Method (*LSEM*), two Maximum Entropy methods (*MaxEnt*1) and (*MaxEnt*2), Cuckoo Search optimization method (*CS*) and Particle Swarm Optimization method (*PSO*)) have been selected and tested to estimate the statistical parameters of wind speed distribution, to calculate the wind power curve in order to assess the performance and the reliability of wind turbines from two sites in Morocco: (Dakhla et Essaouira) operating in random conditions. Several models used in literature have also been selected and tested. Results show that the developed methodology based on the structural reliability analysis and prediction [14,15], is suitable to improve the effectiveness of a *WTG*. Moreover, the proposed methodology highlights the main variables that affect mostly the performance of wind turbine.

2. Wind energy and turbine characteristics

2.1. Wind speed distribution modeling

The first fundamental step in assessing wind power potential consists of the statistical analysis of the wind speed in the selected sites. The main purpose is to expect the probability of certain wind speeds occurrence. Several models may be found in the literature. Wang et al. [16] reviewed and compared some non-parametric and parametric (unimodal distributions and multimodal distributions) models for wind speed probability distribution. They concluded that the non-parametric Kernel density distribution outperforms all of the selected parametric models in terms of the fitting, accuracy and the operational simplicity. Ouarda et al. [17] found that among the one-component parametric distributions, the Kappa and generalized Gamma distributions provide the best fit to the wind speed data at all heights. However, Ouarda et al. [17] underline that the Weibull distribution performs better than the Generalized Extreme Value and 3-parameter Lognormal. In a later work, Ouarda et al. [18] reviewed different criteria used in the field of wind energy to compare the goodness-of-fit of candidate probability density functions to wind speed records, and discussed their advantages and disadvantages. The 2-parameter Weibull distribution remains the most commonly accepted distribution in the specialized literature on wind energy and other renewable energy sources [19–21]. The general form of Weibull probability density function is given by:

$$f(v) = \frac{k}{c}(\frac{v}{c})^{k-1}\exp\left[-\left(\frac{v}{c}\right)^k\right] \quad (1)$$

where c is the scale parameter, k is the shape parameter and v is the