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Uncertainty analysis of wind energy potential assessment

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A R T I C L E I N F O

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A B S T R A C T

This study presents a framework to assess the wind resource of a wind turbine using uncertainty analysis. Firstly, probability models are proposed for the natural variability of wind resources that include air density, mean wind velocity and associated Weibull parameters, surface roughness exponent, and error for prediction of long-term wind velocity based on the Measure–Correlate–Predict method. An empirical probability model for a power performance curve is also demonstrated. Secondly, a Monte-Carlo based numerical simulation procedure which utilizes the probability models is presented. From the numerical simulation, it is found that the present method can effectively evaluate the expected annual energy production for different averaging periods and confidence intervals. The uncertainty, which is 11% corresponding to the normalized average energy production in the present example, can be calculated by specifically considering the characteristics of the individual sources in terms of probability parameters.

1. Introduction

There is a growing global demand for wind energy production. A lot of studies related to the wind characteristics and wind power potential have been made in many countries in the last decade. Bekele and Palm [1] studied the wind energy potential at four locations in Ethiopia by using the wind data and the hybrid optimization model for electric renewable computer software. Ucar and Balo [2] investigated the wind characteristics of the six meteorological stations in Turkey, and their corresponding annual energy production for the four different wind turbines.

Ackermann and Söder [3] provided an overview of wind energy. They summarized that the variation of the mean power output from one 20-year period to the next has a standard deviation of 10% or less. Petersen et al. [4] have reviewed the boundary layer meteorology for sitting of wind turbines, regional wind resource assessment, and short-term prediction of the wind resource. Montes and Martin [5] have indicated that the existence of high levels of uncertainty might represent an obstacle to obtaining financing for wind farms. To overcome the problem, they suggested the statistical simulation methods to calculate the density function of profitability from the probability distributions for wind speed.

Lange [6] has investigated the uncertainty of wind power prediction from the forecasted wind speed. He evaluated the probability distribution of a power prediction error based on the probability density function of deviation between the predicted and the measured wind speeds. Pinson and Kariniotakis [7] have studied a methodology for assessing the on-line prediction risk of short-term wind power forecasts. They defined a risk index to evaluate the weather stability and evaluated the probabilities of the occurrence of high prediction errors according to the index. However, the research is limited to estimating the short-term error for wind power prediction from the forecasted wind speed.

Tindal et al. [8] have compared the predicted average annual power productions before construction with those measured during operation. The results for 510 wind farms in Europe and USA indicate that actual annual power has been 93.3% of pre-construction projections, and the predictions have been overestimated. The authors' explanation for the discrepancy was the poor quality of wind data caused by improper measurement. Bastside and Harding [9] have discussed various sources of error and uncertainty in the assessment of wind energy based on their experience.

Lackner et al. [10] have presented a deterministic method for combining uncertainties that arise in assessing the wind resource, and explicitly derived the sensitivity factors for wind speed measurement uncertainty and the Weibull parameters. Fontaine and Amstrong [11] have tested the uncertainty analysis for a wind turbine in Italy by the International Electric Commission (IEC) method and the Monte Carlo analysis. However, they seemed to adopt the standard deviations in the IEC method without investigating the probabilistic characteristics of the parameters.

A prerequisite for the successful development of wind energy and minimization of financial risk is the quantification of the uncertainty of overall wind energy potential prior to the construction of a wind turbine. Wind power prediction is not only dependent on external wind conditions but also on the structural and mechanical performance of the wind turbines systems [12,13].

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Nomenclature

A	blade swept area	PDF	probability density function
AEP	annual energy production	P_R	rated power
a	slope of linear fit line between wind speeds at reference site and target site	P_{wt}	wind power at certain velocity
b	intercept of linear fit line between wind speeds at reference site and target site	R_{UV}	correlation coefficient between two variables, U and V
CDF	cumulative distribution function	T	duration (hours)
c	scale parameter for the Weibull distribution	U	long-term wind velocity at reference site
e	residual for long-term estimation of wind velocity	U_s	short-term wind velocity at reference site
F	cumulative distribution function	V	wind velocity
f	probability density function	$\hat{V}$	estimated long-term wind velocity at target site
f_ρ	probability density function for air density	V_I	cut-in wind velocity of a wind turbine
f_U	probability density function for wind velocity at reference site	V_O	cut-off wind velocity of a wind turbine
f_e	probability density function for the residuals of the long-term estimation of wind velocity	V_R	rated wind velocity of a wind turbine
f_α	probability density function for roughness exponent	V_s	short-term wind velocity at target site
$f_{P_{wt}}$	probability density function for power output	z	height above ground or sea level
f_k	probability density function for Weibull shape parameter	α	surface roughness exponent
k	shape parameter for the Weibull distribution	$\tilde{\alpha}$	representative surface roughness exponent at certain site
MCP	Measure–Correlate–Predict	ρ	air density
		$\tilde{\rho}$	normalized air density by standard air density
		σ	standard deviation
		$(\bar{\ })$	mean of ()
		$(\hat{\ })$	estimated value of ()

The present paper mostly considers the uncertainty caused by external wind conditions.

In general, the IEC method [14], which is a somewhat deterministic approach, has been widely used in the field. This method is based on the assumption that the different uncertainties are independent and can be expressed in terms of the standard deviation of individual input quantity. However, this method does not allow complicated relationships between different uncertain sources. Accordingly, the development of a more sophisticated stochastic method is demanded, that will simulate the behavior of a physical system.

There are various sources that affect the power output of a wind turbine. Some of these are well defined, but others have not been well understood or even recognized until now. The present paper has attempted to determine the uncertainty that arises during wind energy assessment. The purpose of this study is to create a framework for an uncertainty analysis of wind energy potential at a specific site based on probability models for each parameter. To achieve this, this paper presents probability models for the related variables which are sources for assessment of the wind energy potential, and then provides a Monte-Carlo based simulation procedure utilizing the probability models.

2. Wind data at Kwangyang Bay

2.1. Site details

Kwangyang Bay in Chonnam Province is located on the southern coast of the Korean Peninsula and is surrounded by small hills. There are more than 50 years of wind records at the Yeosu Weather Station, which is at the southern entrance of the bay (see Fig. 1a). Since the Yeosu Weather Station is located on the top of a 67 m high hill in front of the sea, the wind velocity at the bay seems to differ from that at the Kwangyang Bay.

An ocean environmental monitoring tower has recently been installed in the center of Kwangyang Bay. The distance between the Yeosu Weather Station and the monitoring tower is approximately 15 km. As shown in Fig. 1b, a 10 m high tower from an average sea level is equipped with an anemometer at 2.5 m above the tower as well as other sensors for measuring ocean environments. The measured data is regularly transmitted to Chonbuk National University through a cellular phone [15].

2.2. Wind velocities

For the assessment of wind energy potential at Kwangyang Bay, hourly mean wind speeds for 288 months (1/1/1983–12/31/2006) have been collected from the Yeosu Weather Station. Data has been acquired over 12 months (1/1/2006–12/31/2006) at the Kwangyang Bay monitoring tower. The correlation coefficient of wind speeds at the two sites in 2006 is 0.737.

Probability densities of wind velocity at the two sites are shown in Fig. 2. As can be seen in the figure, there are a little differences on the probability densities of wind speeds at the two sites as well as according to the length of data. For investigating seasonal effects, the data is segmented into 3-month sets.

3. Wind characteristics and its probability models

3.1. Air density

The addition of water vapor to air reduces the density of the air. The density of humid air may be calculated as a mixture of ideal gases from the air temperature, the relative humidity, and the barometric pressure [14]. Fig. 3 shows the probability density of the air density computed from the measured temperature, relative humidity and atmospheric pressure at Kwangyang Bay in 2006. The horizontal axis of the figure is normalized by a standard air density of 1.225 kg/m^3. From the figure it is found that the probability density of normalized air density can be expressed as the following uniform rectangular distribution rather than the normal distribution. Although the R^2 values are slightly better for the uniform model, the Kolmogorov–Smirnov test [17] of goodness of fitness may confirm the selection of the uniform probability function more concretely.

$$f_\rho(\tilde{\rho}) = \begin{cases} \frac{1}{1.07-0.94}, & 0.94 \leqslant \tilde{\rho} \leqslant 1.07 \\ 0, & \text{otherwise} \end{cases}. \tag{1}$$