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Determination of rated wind speed for maximum annual energy production of variable speed wind turbines

Ahmad Sedaghat[a,*], Arash Hassanzadeh[b], Jamaloddin Jamali[c], Ali Mostafaeipour[d], Wei-Hsin Chen[e]

[a] Department of Mechanical Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran
[b] Department of Mechanical Engineering, University of Wyoming, Laramie, USA
[c] Department of Mechanical Engineering, American University of the Middle East, Kuwait
[d] Industrial Engineering Department, Yazd University, Yazd, Iran
[e] Department Aeronautics and Astronautics, National Cheng Kung University, Taiwan

HIGHLIGHTS

- Rated wind speed is formulated by power curve of wind turbines and Weibull wind distribution.
- A capacity value relates the annual energy production (AEP) to the rated wind speed.
- Variable speed wind turbines are examined for maximizing AEP at different wind sites.
- New charts are produced for selecting suitable rated wind turbines.
- AEP may be improved by 43% by selecting right rated speed wind turbines.

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ABSTRACT

Rated wind speed is recognized as one of the key design factors affecting the overall power production of a wind turbine. No formulation is found in literature to relate the rated wind speed to the wind turbine power curves and the annual energy production (AEP). This paper aims to formulate the suitable rated wind speed for variable speed wind turbines continuously operating at maximum power coefficient for maximizing AEP. A capacity value is introduced which relates AEP to an integral function of the rated wind speed using Weibull distribution of wind speeds and the constant power coefficient of variable speed wind turbines. The capacity values are calculated and presented versus rated wind speeds at different wind classes and Weibull parameters. From the results, the suitable values for the rated wind speeds for maximizing AEP are found which are considerably higher than normally used values and varied from 2 to 5 times of the annual mean wind speed. For instance, for the mean annual wind speed of 4 m/s and the shape factors of k = 1.2, 1.6, 2.0, 2.4, 2.8, 3.2, and 3.6, the converged rated wind speeds are V_{rate} = 20, 19, 14, 12, 10, 10, and 9 m/s, respectively. On this basis, new charts for rated wind speeds are introduced for selecting suitable wind turbines for maximizing AEP. It is concluded that for some selected wind turbines operating at lower rated wind speeds, the AEP may fall below about 43% of actual achievable AEP when employing higher recommended rated wind speeds. Hence, it is shown that selecting the right rated wind speed wind turbines has great impact on overall energy production of a wind site.

1. Introduction

The ever-growing energy demand, concerns over limited fossil-fuel resources and more restricted environmental regulations have made renewable energies very attractable. Wind energy among other renewable energies is one of the most economical sources of electricity production. It has been shown that understanding wind characteristics for short and long periods is an important step in developing the wind energy industry and helps wind turbine manufacturers to improve wind turbine design for specific wind sites [1].

Many efforts have been made towards improving the performance of wind turbines and wind farms. A comprehensive review of wind turbine optimization techniques is given by Chehouri et al. [2] in which a number of works is referred in maximizing of AEP based on using

* Corresponding author.
E-mail address: Sedaghat@cc.iut.ac.ir (A. Sedaghat).

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Nomenclature

A	swept area of rotor
a	induction factor
c	scale factor
C_p	power coefficient
C_V	capacity value
$f(V)$	Weibull distribution function
k	shape factor
P	power
P_{out}	output power
P_{rate}	rated power
R	blade radius
V	wind speed
V_{mean}	mean wind speed
V_{rate}	rated wind speed
V_{rate_cal}	predicted rated wind speed
y	dummy variable for Gamma function
ρ	air density
λ	tip speed ratio
ω	angular velocity
Γ	gamma function
AEP	annual energy production
COE	cost of energy
PDF	probability density function

wind turbine power curve and wind speed distribution. Most of the cited works focused on optimization of aerodynamic shape of airfoils. A lot of different works can be found to maximize AEP [3–5], and to minimize cost of energy (COE) for an individual wind turbine [6,7] or a group of turbines in a wind farm [8,9]. The turbine blade shape is highly optimized and now researchers try to find different ways to increase the AEP from wind turbine and wind farm in order to make the cost of wind energy comparable with other sources of energy. One of the promising ways to increase the energy production of turbine is to determine the suitable initial design parameters such as rated wind speed for wind turbine manufacturer. In addition, determining the suitable rated wind speed can help customers to select the most suitable available turbine for a specific wind site.

The objective of the present study is to fill the above discussed gap and to find the rigid dependency of the annual wind energy generation to the rated wind speed. Then, the suitable rated wind speed can be suggested for maximizing AEP at a specific wind region. In order to do that, the Weibull distribution function and power performance curves of variable speed wind turbines working continuously at their maximum power coefficient are applied.

It is a matter of common observation that the wind is unsteady and random, and in order to calculate the mean power delivered by a wind turbine from its power curve, it is necessary to know the probability density function (PDF) of the wind speed [1]. Different models are proposed to characterize the wind specifications. Among these models, Rayleigh and Weibull distribution functions are widely used to determine wind characteristics in many wind feasibility studies [1].

Many research works have been devoted to improve the models for wind characteristics [10]. Saleh et al. [11] studied different methods to estimate Weibull distribution parameters for wind speed in Zafarana wind farm, Suez Gulf, Egypt. Shu et al. [12] presented a statistical analysis of the wind characteristics and wind energy potential at typical sites in Hong Kong using Weibull distribution model. The variations of mean wind speed, as well as Weibull parameters, were highlighted on various timescales. Masseran [13] used a Markov chain model to study stochastic behavior of wind direction and showed that it had a significant effect on efficiency of wind farms. Alavi et al. [14] investigated the sensitivity of wind speed distribution functions on wind data and identified more robust and accurate models. Shamshirband et al. [15] investigated the application of extreme learning machines for estimation of Weibull parameters more accurately.

Several studies have been carried out to understand the importance of rated wind speeds on energy production of wind turbines. Adaramola et al. [16] evaluated wind potentials along the coast of Ghana and suggested small wind turbines ranging from 50 kW to 250 kW with moderate rated wind speeds of 9–11 m/s could be more suitable for the region. Zhang et al. [17] defined a capacity factor based on the wind speed and wind direction. The importance of both terms on the better estimation of wind energy potential was investigated. In another work, a wind resource map in Thailand was applied to integrate both wind speed and wind direction for cost optimization of a wind farm [18]. Masseran [19] emphasized the effects of wind directions on maximizing efficiency of wind farms. Temporal and spatial variability of wind speeds was studied to show the effects of turbulence on assessment of wind resources [20]. The wind energy potential in southern Caspian Sea is studied by Amirinia et al. [21]. They applied uncertainty analysis in their work.

Specifying rated wind speed is an important factor for manufacturers and costumers. The rated wind speed is classically selected by a value between 1.5 and 2 times of the annual mean wind speed, or related to the annual mean cubic wind speed. The annual mean cubic wind speed is defined as [22]:

$$V_{meancubic} = \sqrt[3]{\int V^3 f(V) dV}\,(m/s) \tag{1}$$

Selecting the annual mean cubic wind speed as the rated wind speed, however, does not include the effects of the rotor power performance of a wind turbine. The power performance depends on a wind site characteristics as well as the rotor parameters. The rotor parameters are aerofoil type, the design tip speed ratio, rated wind speed, rotor diameter, and blade geometry of a wind turbine which summarizes into the power coefficient curve of the wind turbine [23].

To our best of knowledge, only a few works [22] have been carried out to determine the suitable rated wind speeds for a wind turbine to produce its maximum power. In Ref. [22], the AEP related to the annual mean wind speed and a factor k using the one parameter family of Rayleigh distribution function for stall regulated wind turbines. In the present work, the new equation is introduced for the capacity value and the different model (two variable model) is employed. The model is developed to specify the suitable rated wind speed for a variable speed wind turbine.

This paper is arranged by giving the most recent reviews on improving wind assessment methods and enhancing energy production of wind turbines in the Section 1. Then, a mathematical model for estimating annual wind energy versus rated wind speed of some continuously variable speed wind turbines is introduced in the Section 2. In this section, power curves of the wind turbines are integrated with the Weibull distribution to obtain a capacity value as an integral function of the rated wind speed. Results of the proposed modelling are presented in the Section 3 and a useful wind chart is generated for selecting the suitable rated wind speed based on wind characteristics of a specific region. Finally, in the Section 4, the conclusions are made and the recommended rated wind speeds for several wind regions in the State of Kuwait are given.

2. Environmental wind characteristics

In this study, the widely used two parameters family of the Weibull distribution function is used which is defined by [1]: