Energy 73 (2014) 88–95

Contents lists available at ScienceDirect

Energy

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

Comparative analysis on power curve models of wind turbine generator in estimating capacity factor

Tian-Pau Chang [a,*], Feng-Jiao Liu [b], Hong-Hsi Ko [a], Shih-Ping Cheng [b], Li-Chung Sun [b], Shye-Chorng Kuo [a]

[a] Department of Multimedia Animation and Application, Nankai University of Technology, Taiwan
[b] Department of Electrical and Information Technology, Nankai University of Technology, Taiwan

ARTICLE INFO

Article history:
Received 17 November 2013
Received in revised form
23 May 2014
Accepted 25 May 2014
Available online 8 July 2014

Keywords:
Wind energy
Wind turbine
Power curve model
Capacity factor
Weibull function

ABSTRACT

The capacity factor is an essential indicator in evaluating a wind turbine's efficiency. In this paper, four kinds of power curve models—linear, quadratic, cubic, and general—are applied to estimate the capacity factor of a pitch-controlled wind turbine based on the Weibull probability distribution of wind speed. The general model is adopted for the first time in this issue. The wire-frame graph of capacity factor is demonstrated for practical Weibull shape and scale parameters representing various wind farms. To analyze the validity of the four empirical models, seven power output curves provided by different manufacturers are selected for different operating speeds. The results show that a turbine generator installed at a wind site with larger scale and shape parameters may show greater performance, but limitations do exist. The capacity factors calculated from manufacturer data are far greater than those from empirical models if the cut-in, rated, and furling speeds of a wind turbine are set as 4, 15, and 25 m/s, respectively. Similar values from empirical models get closer to those from manufacturer data when the cut-in or rated speeds decrease. The quadratic model shows better agreement with manufacturers' power curves.

1. Introduction

Due to the shortage of fossil fuels and the need to protect the environment, the utilization of renewable energy is being paid greater attention all over the world. In this context, wind energy is one of the most promising energy resources. It can be converted to electrical power through wind turbine generators. The amount of electrical power generated by a wind turbine at a particular wind farm depends on factors such as the wind speed distribution, turbine specifications, turbine conversion efficiency, and the maintenance situation [1–7].

The Weibull probability density function is widely used to estimate the wind energy potential [8–18]. When evaluating a turbine's performance, the capacity factor, which is defined as the ratio of average power generation of a turbine to its rated generation, is usually employed in engineering practice [19–27]. There are basically two types of wind turbine generators on the market, namely stall-controlled and pitch-controlled generators. In this research, the pitch-controlled generator is studied. Fig. 1 shows typical power output versus wind speed [28,29]. The power output increases with wind speed in the non-rated region between cut-in speed (v_c) and rated speed (v_r), while the rated power remains constant in the rated-region between the rated and furling speeds, v_f (note that the furling speed is called cut-out speed in some literature). The turbine will be shut down to prevent damage if the wind exceeds the furling speed.

For estimating the capacity factor, several empirical models, such as the linear model [30], quadratic model [1–3], and cubic model [22,24,25], were used to approximate the behavior of the power output curve in the non-rated region in previous research studies. However, these studies did not present detailed validity comparisons between the models for various wind speed conditions. In this paper, a validity comparison to another model (named the general model) is incorporated, which is applied to the issue for the first time.

Meanwhile, seven power output curves released by different manufacturers will be selected for comparison with those empirical models to determine the most suitable model (see Table 1). The manufacturer data is demonstrated as a discrete series of power values versus wind speeds. These values are fitted using a sixth-

* Corresponding author. Fax: +886 49 2561408.
E-mail address: t118@nkut.edu.tw (T.-P. Chang).

http://dx.doi.org/10.1016/j.energy.2014.05.091
0360-5442/

Nomenclature

A	sweep area of turbine rotor (m^2)
a_i	polynomial coefficient
CF	capacity factor, dimensionless
C_p	power coefficient of turbine
c	Weibull scale parameter, m/s
f	Weibull probability density function
k	Weibull shape parameter, dimensionless
P	power output of turbine
P_{avg}	average power of turbine
P_n	non-rated power coefficient of turbine
P_r	rated power of turbine
v	wind speed, m/s
v_c	cut-in speed of turbine, m/s
v_r	rated speed of turbine, m/s
v_f	furling speed of turbine, m/s
Greek letters	
ρ	air density, kg/m^3
Γ	Gamma function
γ	incomplete Gamma function

order polynomial to obtain a continuous curve before calculating the capacity factor. All the calculations of the capacity factor are based on the Weibull distribution of wind speed. The wire-frame graph of the capacity factor is shown for a wide range of Weibull parameters representing different wind sites. In addition, the level of operating speeds of a wind turbine might affect its performance and different cut-in speeds and rated speeds will be discussed in the subsequent analyses. By the method proposed in this paper, an engineer could choose the best wind turbine for a given wind site or vice versa.

2. Weibull function

The Weibull function has commonly been used to characterize the wind speed distribution. Its probability density function is given as [8–18]:

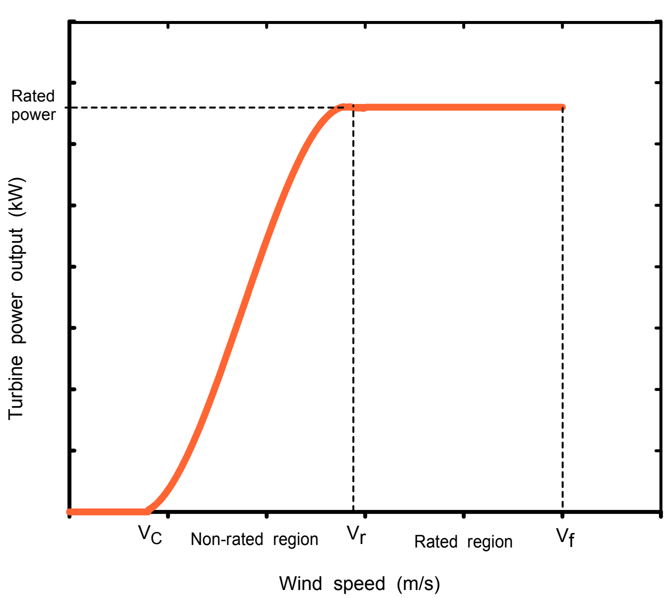

Fig. 1. Typical power output curve of pitch-controlled wind turbine generator.

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

where v is the wind speed, k is the dimensionless shape parameter, and c is the scale parameter, which has the same units as the wind speed. The Weibull shape parameter reflects the width of data distribution, and the larger the shape parameter is, the narrower the distribution will be. The scale parameter controls the abscissa scale of a plot of data distribution.

3. Turbine power output

The power output of a wind turbine generator can be expressed as:

$$P(v) = \frac{1}{2} C_p A \rho\, v^3 \tag{2}$$

where C_p is the power coefficient of the turbine (*i.e.*, electricity produced by the wind turbine/total energy available in the wind), A is the swept rotor area of the turbine, and ρ is the air density. For a pitch-controlled turbine, the power output curve shown in Fig. 1 can be characterized by the non-rated region (for wind speeds between v_c and v_r) and the rated region (for wind speeds between v_r and v_f). In the rated region, the power remains constant and is defined as the rated power P_r. The turbine is shut down when the wind speed exceeds v_f to prevent damage. The power curve can be written as:

$$P(v) = P_r \begin{cases} 0 & v < v_c \\ P_n(v) & v_c \le v < v_r \\ 1 & v_r \le v \le v_f \\ 0 & v > v_f \end{cases} \tag{3}$$

where $P_n(v)$ is the normalized power output value in the non-rated region.

The average power yield, based on the Weibull probability density function, is given by:

$$\begin{aligned} P_{avg}(v) &= \int_0^\infty P(v) f(v) dv \\ &= P_r \int_{v_c}^{v_r} P_n(v) f(v) dv + P_r \int_{v_r}^{v_f} f(v) dv \end{aligned} \tag{4}$$

4. Capacity factor for different power curve models

The capacity factor (CF) is defined as the ratio of average and rated power:

$$\mathrm{CF} = \frac{P_{avg}(v)}{P_r} \tag{5}$$

Four empirical models and seven manufacturer-provided models considered in this research are described below:

4.1. Linear model

For the linear model, the relationship between the power output and wind speed in the non-rated region is linear (similarly, it is quadratic and cubic for the quadratic and cubic models, respectively). The normalized power output in the non-rated region, $P_n(v)$, is expressed as [30]: