Rated Wind Speed Reality or Myth for Optimization in Design of Wind Turbines

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Rated Wind Speed Reality or Myth for Optimization in Design of Wind Turbines

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Abstract— **The rotor design procedure of wind turbines starts first with adopting a rated output power and a rated wind speed. There is lack of modelling to determine an optimized rated wind speed and no evidences are observed to suggest the best rated wind speed to produce maximum output power annually. For example in the market of small wind turbines, it is frequently observed that the rated wind speed is taken from small value of 8 m/s to large value of 20 m/s. To examine overall performance of these wind turbines, it is required to develop mathematical models to relate the annual power production of the wind turbines to the given rated wind speeds. By examining power curves of some small European wind turbines from 100 to 900 Watt with constant speed generators, a simplified mathematical model for power curves is introduced and combined with Weibull distribution of wind speeds. Results of the model based on a capacity factor are presented versus the rated wind speed using wind characteristics of an optional region. It is observed that between the cut-in and cut-out wind speeds, there is an optimum rated wind speed above which the annual output power production of the wind turbine remains unchanged.**

Keywords— ***power performance; rated wind speed; Weibull distribution; wind energy; wind turbine.***

I. INTRODUCTION

Wind turbine industry is growing worldwide due to environmental issues and governments actions to remedy these [1-3]. Small wind turbine market is growing slowly; however, they will have great impact in future large wind turbine design and development [4-11]. The small wind turbine provides the very feasible systems for amending and testing in different environmental wind characteristics. The urban wind networks supported by Intelligent Energy of Europe have provided a catalogue of the European urban wind turbines of small wind turbine manufacturers [12]. Figure 1 shows a selective of these wind turbines power curves versus wind speed which operate with constant speed generators.

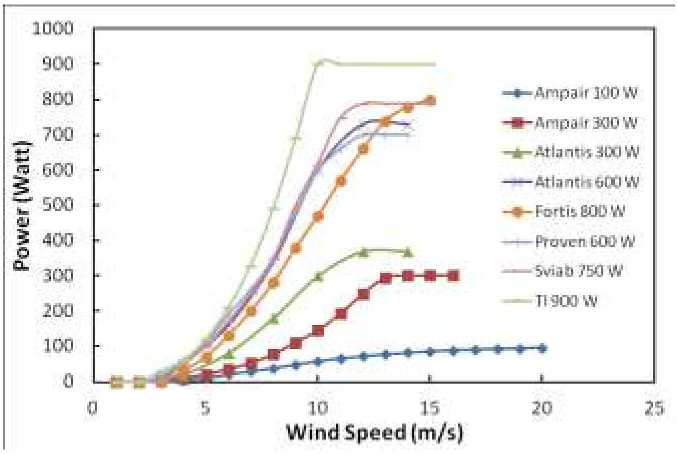

Fig. 1: The power curves of some European small wind turbine brands.

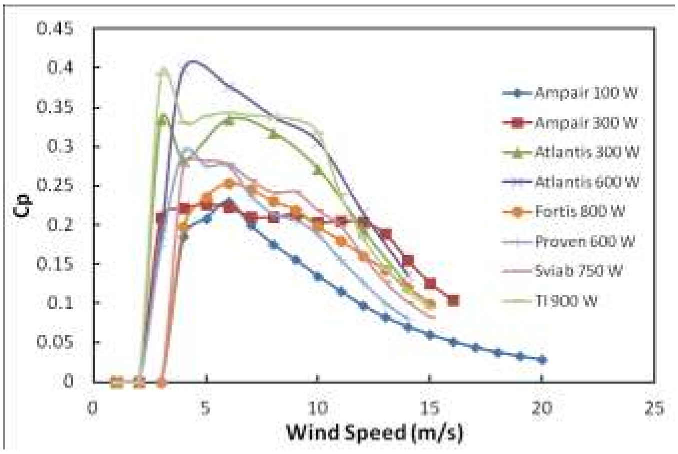

Fig. 2: The power coefficient of the European small wind turbine brands.

As observed in Figures 1 and 2, the small wind turbine manufacturers have come up with different cut-in and cut-out wind speeds and from the catalogue [12] they have provided different rated wind speeds from 8 m/s to 20 m/s.

Figure 2 shows the power coefficient of the same wind turbines defined by:

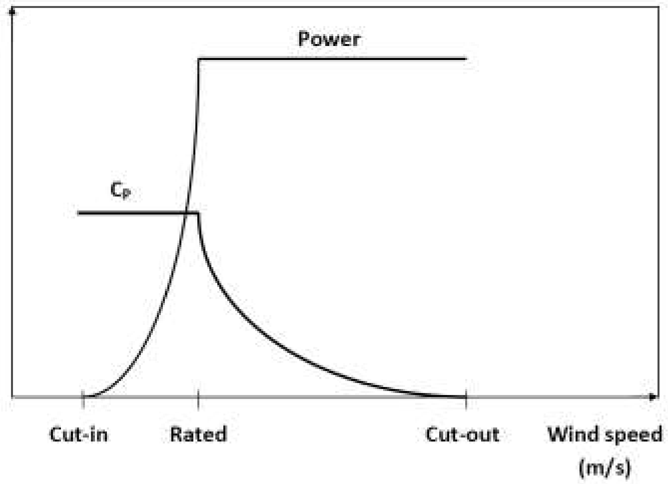

Fig. 3: The schematic of the power curves for a typical small wind turbine with constant speed generator.

$$C_P = \frac{P}{\frac{1}{2}\rho A_{rotor} V^3} \tag{1}$$

In the above relation (1), P is the output power (Watt), ρ is the air density (kg/m^3), A_{rotor} is the rotor span area (m^2), and V is the wind speed (m/s).

Rated wind speed is defined as the wind speed at which the rated power (the maximum output power) of the electrical generator is reached [13].The designed rotor swept area and the corresponding blade lengths are directly related to the rated power and inversely to the selected rated wind speed. Hence, it is usually advantageous to have a high design tip speed ratio [13]. The design tip speed ratio is the first parameter in blade design decided depends on airfoil shapes of the blade and blade numbers which is generally taken as 6-8 in modern wind turbines [14, 15].

For new designers and developers of wind turbines, as observed from the relation (1), the rated wind speed and the rotor area are inversely dependent, which means larger rated wind speed selection in design stage will result in smaller rotor diameter and vice versa. Hence, it is crucially important to select the rated wind speed as large as possible to reduce the size of rotor which consequently reduces manufacturing costs. Smaller rotor size and larger rated wind speed also means higher rotational speed of the electrical generator. Therefore, some compromise should be made between the selection of rotational speed of an electrical generator and the suitable rated wind speed in such a way that guarantee maximum annual power output of the wind turbine for a site specific turbine [16, 17].

Tang et al. [18] have investigated the suitable rated wind speeds using the one parameter family of Rayleigh wind distribution.

II. Mathematical modelling

In this study, the two parameter family of the Weibull wind distribution function is used which is defined by [13]:

$$f(V) = \left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1} exp\left[-\left(\frac{V}{c}\right)^{k}\right] \tag{2}$$

In the Weibull relation (2), k is the shape factor and c is a scale factor (m/s). The dimensionless shape factor, k, is normally obtained by fitting Weibull function to the measurements of wind speeds using wind masts for duration of 3 months to one year through 10 minutes intervals. Here, we assume different k values and average wind speeds V_{mean} as known parameters and determine the scale factor c (m/s) as follows:

$$c = \frac{V_{mean}}{\Gamma\left(1+\frac{1}{k}\right)} \tag{3}$$

The gamma function is defined as $\Gamma(x) = \int_0^\infty exp(-y) y^{x-1} dy$.

For the power performance of small wind turbines with constant speed generators, the simplified model is introduced for the cut-in wind speed of 2.5 m/s and cut-out wind speed of 25 m/s as shown in Figure 3 such that the power coefficient remains constant to the value of rated power coefficient between cut-in and rated wind speeds while the output power remains constant above rated speed till cut-out wind speed. However, the propose approach follows below can be equally employed using any power curve of a wind turbine and any optional cut-in and cut-out wind speeds.

The annual power production of the modeled wind turbine in the form of a capacity factor (CF) in (m/s)^3 is calculated versus the rated speed, V_{rate}, by:

$$\mathrm{CF} = \frac{P_{annual}(MWh)}{10^{-6}.8760.\frac{1}{2}\rho A_{rotor} C_{Prate}} = \int_{cut-in}^{rated\ speed} V^3 f(V) dV + V_{rate}^3 \int_{rated\ speed}^{cut-out} f(V) dV \tag{4}$$

The results of this capacity factor versus rated wind speed at different wind conditions are presented and discussed in the next section. The capacity factor is independent of the power coefficient value and the rotor area so that the outcome will be showing important effects of wind characteristics in power output of wind turbine with relation to only the designed rated wind speed.

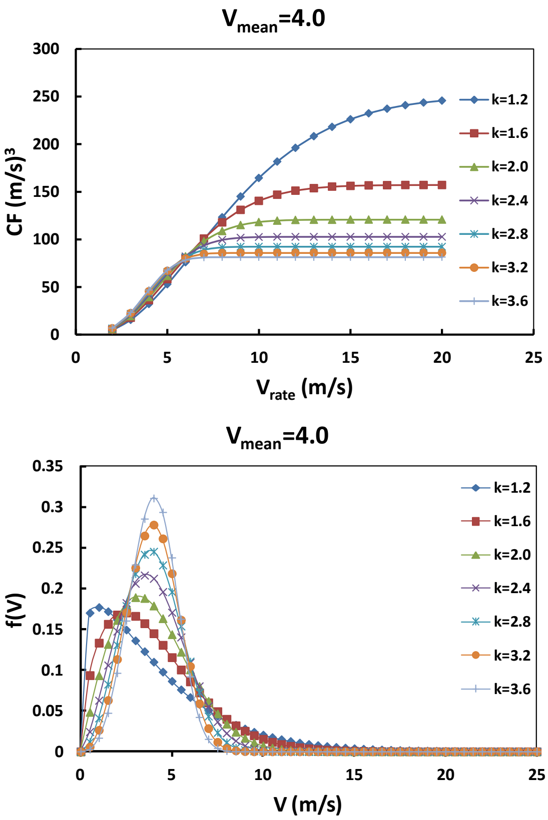

Fig. 4: The schematic of the power curves (top) and Weibull distributions (bottom) at the average wind speed of 4 m/s.

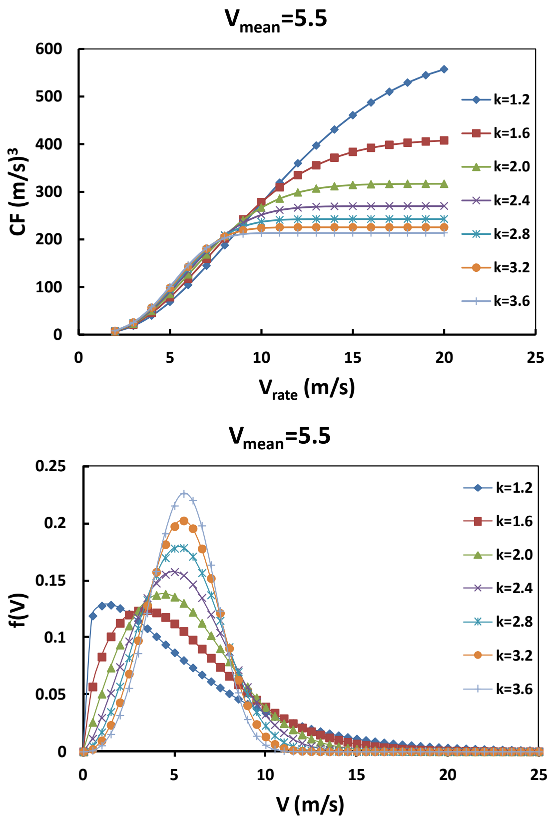

Fig. 5: The schematic of the power curves (top) and Weibull distributions (bottom) at the average wind speed of 5.5 m/s.

III. Results and Discussions

Figure 4 shows the results of the capacity factor, expressed by relation (4), and the Weibull distributions, given by equation (2), for the annual mean wind speed of 4 m/s and the shape factor values of k=1.2, 1.6, 2.0, 2.4, 2.8, 3.2, and 3.6. Depend on the values of the shape factor, the maximum capacity converges at rated wind speeds of V_{rate}=20, 19, 14, 12, 10, 10, and 9, respectively. This means, for the mean annual wind speed of V_{mean}=4 m/s, the rated wind speed varies from $V_{rate}=2.25*V_{mean}$ to $V_{rate}=5*V_{mean}$ depending on the value of the shape factor k. Shape factors above k=2 has shown nearly normal distribution.

Figure 5 shows the results of the capacity factor versus rated wind speed and the Weibull distributions for the annual mean wind speed of 5.5 m/s and the same shape factor values. As observed in Figure 5, the capacity factor converges to its maximum value at $V_{rate}=2.18*V_{mean}$ to $V_{rate}=4.44*V_{mean}$. For the k value of k=1.2, the capacity factor does not converged to the maximum value. For the smaller shape factors the distribution are skewed and the capacity factor posses significantly higher values.

Figure 6 shows the results of the capacity factor at the annual mean wind speed of 7.5 m/s producing high capacity factor for all the shape factor values. At this high wind speed region, a few curves of capacity factors have converged to the maximum values. From Figure 6, it is observe that the optimum rated wind speeds may vary between $V_{rate}=2.13*V_{mean}$ to $V_{rate}=3.33*V_{mean}$.

IV. Conclusions

The power performance of small wind turbines are strongly dependent on the design value of rated wind speeds. In this study, a capacity factor is introduced by modelling power curves of some small European wind turbines. The capacity factor is expressed as a function of the rated wind speed; i.e. CF(V_{rate}). In the simplified model, the capacity factor is independent of the power coefficient value and the rotor area. Hence by maximizing the capacity factor versus the rated wind speed, an optimum rated wind speed was obtained according the wind region characteristics.

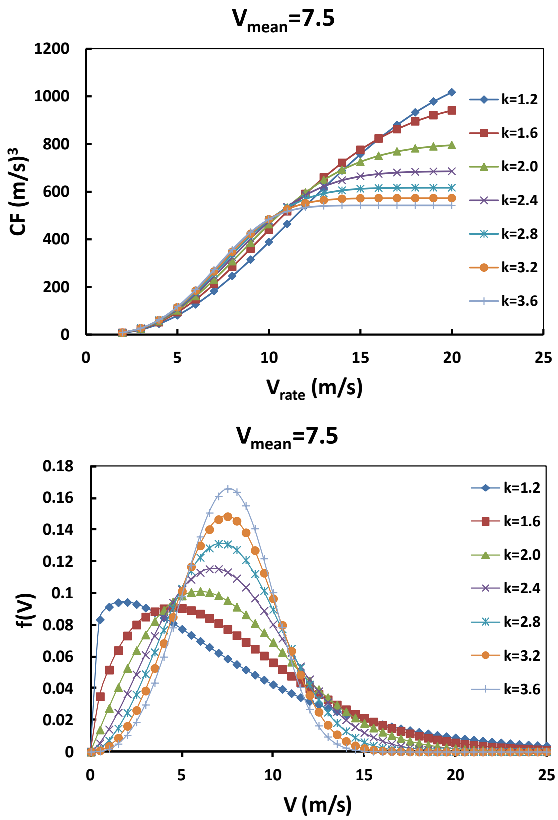

Fig. 6: The schematic of the power curves (top) and Weibull distributions (bottom) at the average wind speed of 7.5 m/s.

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