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The ideal power curve of small wind turbines from field data

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ABSTRACT

The present study aims at assessing the ideal power curve of fixed-speed, passive stall, small horizontal axis wind turbines from turbulent field data. The ideal power curve refers to ideal conditions (e.g., the wind is steady, laminar, spatially uniform and undisturbed by the turbine; no yaw error; the power output is intended in steady state). The ideal power curve has two main applications: the prediction of the wind energy that can be captured and the extension of the power curve to sites having different turbulence levels from the primitive test site.

A 12 kW fixed-speed wind turbine was monitored for two years in a fairly turbulent site; the power train of the turbine had no appreciable filtering effect on the wind fluctuations. The ideal power curve was analytically derived by a Taylor's expansion (whose convergence was enhanced by the Shanks' transformation) and by an accurate analytical assumption of the ideal power coefficient.

The present analytical solution is easy to handle and compared successfully to the IEC-based curve. The turbulence increases/diminishes the power output for velocities less/greater than the velocity at the inflection point of the power curve. Energy predictions by the ideal curve are within the inherent experimental error.

1. Statement of the problem

The power curve of a wind turbine is the function that characterizes the overall performance of the machine. Its knowledge is important to make predictions of the energy that can be captured in a site; to make comparisons among concurrent machines and to monitor the turbine efficiency over years of production. An objective (machine-specific) power curve shall not depend on the turbulence of the test site. According to the international consensus, the only way to correctly investigate wind turbines is by field tests; both American and European standards do not consider performance measurements taken in wind tunnel tests or truck tests.

The power curve of a wind turbine derived by field tests, however, is unavoidably plagued by many factors, in particular the turbulence existing at the first calibration site; as a result, the application of the power curve to other sites, whose turbulence is different from the primitive test site, is questionable.

The power curve displays the relation between the electrical power output produced by the wind turbine, P_o, and the reference wind velocity V:

$$P_o(V) = \tfrac{1}{2}\rho A V^3 C_{p_o}(V), \quad (1)$$

where ρ is the mass density of the air; A is the area swept by the rotor; and C_{p_o} is the ideal power coefficient, a function of V, that encompasses also the electrical and mechanical efficiencies of the turbine.

Eq. (1) is here introduced to describe idealized conditions (e.g., the wind is steady, laminar, spatially uniform and undisturbed by the turbine; no yaw error; the power is intended in steady state); since the above hypothesis cannot possibly be found in the real world, Eq. (1) is hereinafter referred to as the *ideal power curve*, P_o; it is the smooth reference curve that would originate from wind tunnel tests.

As mentioned, the straightforward use of Eq. (1) in field installations is hardly meaningful: in fact, the upstream approaching turbulence is one of the most important factor for data scattering and this generates inaccuracies in energy predictions based on Eq. (1).

The components of the performance assessment of wind turbines, including the site calibration, were analyzed by Frandsen et al. (2000), who introduced the concepts of the extended power curve (though it may prove difficult to apply) and also of the reference power curve, which is based on reference input variables.

This study is different in that it extracts the ideal power curve P_o from the actual power curve measured at the test site; it is also aimed at verifying to what extent the inaccuracies of the power curve are actually important in estimating the annual energy production (AEP).

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Nomenclature

A	swept area by the rotor (m^2);
C_p	actual power coefficient (−);
C_{p_o}	ideal power coefficient (−);
G	shear rate (m^{-1});
$I=\sigma_u/V$	turbulence intensity (−);
P_G	power output at the generator (kW);
P_o	ideal power curve (kW);
V	reference wind velocity (m/s);
V_{in}	cut-in velocity (m/s);
$w=V/V_{in}$	dimensionless wind velocity (−);
β	scale factor (−);
ρ	mass density of the air (kg/m^3);
σ_u^2	variance (m^2/s^2);
AEP	annual energy production (kWh);
agl	above ground level;
GW	12 kW fixed-speed wind turbine;
IEC	International Electrotechnical Commission;
SS	soft starter.

2. Characterization of the test site

Since the quality of field data is crucial to obtain reliable power curves, this section and appendix (B) will explain in detail the equipment and the procedure adopted for data collection and processing. The guidelines IEC 61400-12-1 (2005) were strictly followed in this study.

The experimental data were collected in the Adige valley, which is oriented along the North–South direction (Fig. 1); the test site is located in a flat terrain, the industrial estate of Trento city; buildings (maximum height 20 m) are disseminated around the test site, apart from the East sector covered by apple trees and a few small houses. A powerful thermal wind originates from the lake of Garda and blows transversal to the Adige valley (e.g., from the West direction); the test site is located 1 km downwind a sudden enlargement due to a steep cliff whose elevation is 350–500 m above the test site.

The mean annual wind velocity is 2.65 m/s, even lower than the cut-in velocity (3 m/s) claimed by the manufacturer of the GW turbine (Fig. 2); however, the central part of the day showed an average wind speed greater than 7 m/s with a maximum 10-min intensity as high as 17 m/s. The layout of the test site helped in minimizing mutual wake effects among turbines and masts. Meteo masts suffered no wake effects for the most frequent (*NNW*) and the most energetic (*WSW*) wind sectors. Both meteo masts were equipped with one cup anemometer and a wind vane at hub height 18 m_{agl} (above ground level) and another cup anemometer at 9 m_{agl}. An hygrometer, a thermometer, a pluviometer and a barometer were installed on the GW mast at 17 m_{agl}; an ultrasonic 3D anemometer was also operating for one month (June) at 18 m_{agl} on the GW mast and it was used for the spectral analysis of the turbulence. The technical specifications of the measuring equipment are fully reported in Appendix B.

The main characteristics of the wind turbines are:

(1) *GW turbine*: rated power 12 kW at 9.5 m/s; rated speed 1030 *rpm*; downwind, two bladed, grid connected; rotor diameter 13 m; cut-in velocity 3 m/s; cut-out velocity 25 m/s; passive stall; fixed-speed, 6-pole asynchronous generator; hub height at 18 m_{agl}. Since this turbine operated with no active controls, it was particularly suitable to understand turbulence effects without the filtering action of the controls; and

(2) *JT turbine*: rated power 20 kW at 12 m/s; upwind, three bladed, grid connected; rotor diameter 8 m; pitch-regulated control; variable speed with synchronous generator; hub height at 18 m_{agl}.

A micro turbine was also operating in stand-alone configuration (rated power 1 kW at 12.5 m/s; upwind, three bladed, rotor diameter 1.8 m; variable speed with synchronous generator; hub height at 9 m_{agl}); it helped in providing a further check to clarify doubtful data.

Both turbines had their own dedicated meteo mast at a distance of 2.5 rotor diameter. GW and JT were both equipped with sensors to monitor structural and functional parameters (e.g., pitch angle; rotor location; angular speed; yaw angle; acceleration; shaft rotational speed; flapwise moment; thrust and torque); sensors and data acquisition systems are detailed in Appendix B.

Ambient data (wind velocity and direction; atmosphere pressure and temperature) were acquired at 0.5 Hz, while power and other turbine data at 1 kHz; both average and standard deviation of the above data were calculated over each 10-min period, disregarding mast data that happened to be taken in the turbines'

Fig. 1. GW turbine, 12 kW, fixed-speed, two bladed, downwind (*right*); JT turbine, 20 kW, three bladed, upwind (*left*); the view is from South to North.