The influence of wind shear in wind turbine power estimation

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***Abstract*—Power curve measurement for large wind turbines should take into account more parameters than only the wind speed at hub height. To identify the influence of wind shear on wind turbine performance, wind speed measurements in different heights are analysed. The logarithmic and power law equations, which are commonly used to depict the increase in wind speed with height, are tested with real measurement data. The measurements have been performed using a remote sensing equipment, specifically a LIDAR one, due to its ability for measuring wind speed at several heights at the same time. In order to assess the power curve performance of a commercial wind turbine, energy production data for a test period of three months are also used. The suitability of representing the actual energy flux through the rotor with an equivalent wind speed instead of wind speed measured just at hub height is examined.**

I. Introduction

In contrast to conventional power plants, the production of wind farms depends on meteorological conditions, particularly the magnitude of the wind speed, which can not be directly influenced by human intervention. Thus, in wind energy systems, wind speed plays the most important role when the energy produced by a wind energy conversion system is assessed. Due to the cubic relationship between velocity and power, it is expected that a small variation in the wind speed will result in a large change in power. Therefore it becomes quite important analyzing the variations of the wind speed in front of the wind turbine.

In the past, wind data were measured and evaluated almost exclusively from a meteorological point of view, [1]. However, these data are not sufficient when one is considering the commercial exploitation of wind resources by means of wind turbines. The earlier meteorological data do not provide much detailed information about the increase of wind speed with height or the local wind conditions of a particular terrain. It is only in the past two decades that extensive wind measurements have been carried out with consideration of the particular aspects relating to the use of wind turbines. Nowadays, it is known that the power curve of a wind turbine depends upon a large number of meteorological and topographic parameters, among them, wind shear is one of the most important parameters that influence the uncertainty of the power curve measurements, [2]–[9].

The uncertainty of power performance measurements is closely related to the uncertainty of the wind speed measurement. In the latest edition of the international standard for power performance, [10], the wind speed at hub height is the primary input parameter for power curve measurements, therefore wind speed at hub height is the only reference of wind speed over the whole turbine swept rotor area. This method has no major relevance for smaller wind turbines, but the measured results show that large multi-MW turbines could be exposed to highly varying wind conditions. Hence, the measurement of the wind speed at more heights within the swept rotor area provides a better knowledge of the wind profile, just like a better estimation of the energy produced, than the measurement based only on the hub height speed.

While the uncertainty reduction in the measurement of the power curve is desirable, the use of higher met masts in order to reach above hub height causes several difficulties, both technical and financial, and seems that it can only be achieved by the use of remote sensing instruments like LIDARs. In [5], [7], [8], wind speed measurements at several heights below hub height were performed and was concluded that it is not sufficient to measure the wind speed at the lower rotor part and extrapolate it at the upper part.

The aim of the present study is to investigate, through measurements performed on a meteorological mast and a LIDAR equipment, and taking into account the energy produced by a wind turbine located closeness to the preceding equipments, how much the scatter in power curve measurement can be reduced. Thus, in section II a brief description of the test site and wind resource features are shown. Next, section III analyses in depth concepts about wind shear and its application on the present work. Section IV studies the suitability of using

The authors would like “Junta de Comunidades de Castilla-La Mancha” (PAI08-0145-9976) and “Ministerio de Ciencia e Innovación” (ENE2009-13106) for the financial support.

an equivalent wind speed taking into account the wind speed measured at the whole rotor swept area. Finally, section V analyses the influence of wind shear in the power produced by the wind turbine and section VI summarizes all the ideas found in the work.

II. Test site

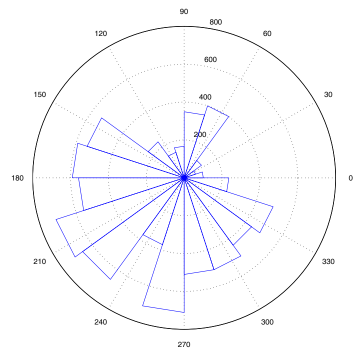
A WindCube LIDAR equipment has been used in an experimental test covering a period of three months. The test was done in a wind farm located in the south of Spain (due to confidentiality issues it is not allowed to clarify the location more exactly). The LIDAR was installed next to a meteorological mast, at a distance lower than 30 m, thus the values recorded by both equipment may be used in the same way, [11]. The wind turbine was located at 300 m of distance from the wind speed meters. Table I shows the measurement heights for both equipment and figure 1 the layout.

Met Mast	LIDAR
30.7 m	40 m
64.5 m	64 m
67 m	67 m
	87 m
	107 m
	117 m
	127 m
	137 m
	200 m

TABLE I
MEASUREMENT HEIGHTS FOR WIND SPEED

Fig. 1. Equipment at test site: WindCube (front) and Met Mast (back)

The first task when an assessment of power curve performance is going to be performed, is to justify the topographical features of the terrain. According to [12], when the differences in elevation exceeded 60 m within a radius of 11.5 km in the surroundings of the wind turbine, that terrain must be considered as complex terrain. Thus, it can be concluded



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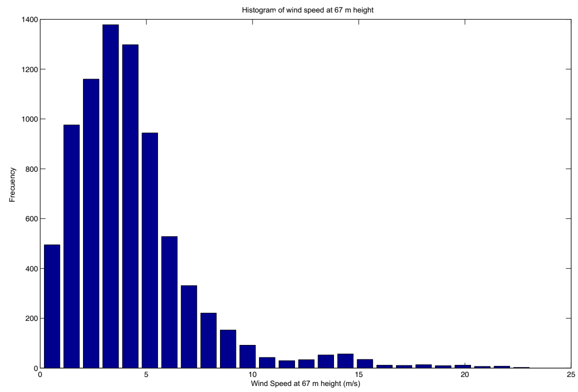


(b)

Fig. 2. Wind resource features at test site

that the terrain over all the measurements were performed is a complex one. Moreover, it must be pointed out that the topography is a very uncommon one due to its complexity.

Although the main object of the present paper is to analyze the infliuece of wind shear in wind turbine performance, an slight description of the wind resource at test site is depicted in figure 2. The wind farm is located at less than 10 km from the sea, and southwest direction is recorded as the main wind speed direction, figure 2a. In figure 2b a histogram shows the frecuency of wind speeds taken at 67 m height.

III. Wind shear

The friction of the moving air masses against the earth's surface slows down the wind speed from an undisturbed value at great altitude (geostrophic wind) to zero directly at ground level, [1]. The flow of air above the ground is retarded by frictional resistance offered by the earth surface (Boundary Layer Effect), [13].

The instantaneous increase in wind speed with elevation depends on several meteorological factors, which determine the atmospheric stability. However, the mean value to be expected statistically over a long term at a particular height is largely determined by the roughness of the earth's surface. The surface roughness of a terrain is usually represented by the roughness class or roughness height, z_0, and its values vary between 0 and 5, [1], [13]–[15], according to the smoothness or roughness of the terrain, respectively.

A conventional approach to depict the increase in wind speed with height is the logarithmic height formula:

$$\bar{v}_H = \bar{v}_{ref} \cdot \frac{ln\frac{H}{z_0}}{ln\frac{H_{ref}}{z_0}} \qquad (1)$$

where:

- $\bar{v}_H$ = mean wind speed at elevation H, (m/s)
- $\bar{v}_{ref}$ = mean wind speed at reference elevation H_{ref}, (m/s)
- H = height (m)
- H_{ref} = reference height (m)

Eq. (1) could be more complicated to use in some cases than the so-called *Power Law* aproximation, according to Hellman, which is sufficient for many engineering tasks:

$$\bar{v}_H = \bar{v}_{ref} \cdot \left(\frac{H}{H_{ref}}\right)^{\alpha} \qquad (2)$$

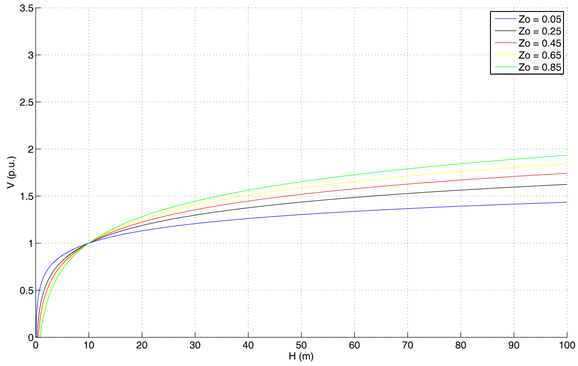
where, $\bar{v}_H$, $\bar{v}_{ref}$, H and H_{ref} were defined in equation (1), and α is Hellman's exponent or shear exponent. As a basic idea, it must be said that the previous equations produce different results. Though, both of them have the same technical concept: at wind speeds below reference height, the obstacles in the terrain (equal to say "greater roughness height") will produce a decrease in wind speed. Whereas at wind speed over reference height, the larger the roughness height, the greater wind speed, figure 3. In [16] it is formulated that equation (2) offers a nearly perfect fit to equation (1) under atmospheric stable conditions for certain surface roughness conditions and a good approximation under neutral and unstable conditions in the limit of very smooth surfaces.

A. Measured wind shear

The analysis is carried out using data from the WindCube located at test site for a 3 months period. WindCube equipment measures wind speed and direction at 9 heights once a second. Then, the 10 min. average value is chosen because the energy contained between the 10 min. and 5 hours period is quite small, [14]. Figure 4 shows wind speed recorded during the test period at the measurement heights depicted in table I, and table II shows the mean wind speed, thus it can be deduced that a mean wind shear with low roughness height or high unstability degree is found at test site.

4.58	4.71	4.73	4.85	4.99	5.05	5.12	5.18	5.34

TABLE II
MEAN WIND SPEED (M/S)



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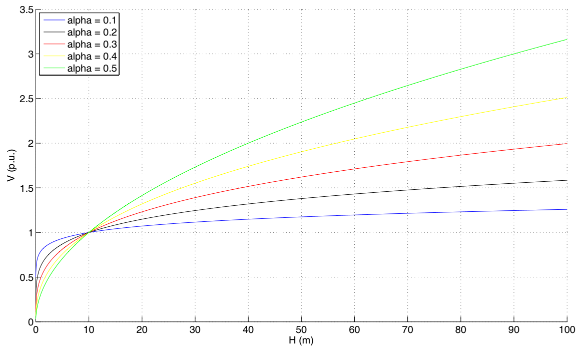


(b)

Fig. 3. Logarithmic and Potential Law

In figure 5, the shear exponent between different couples of heights is calculated during the test period according to equation (2). It is shown a very characteristic diurnal variation during the whole measurement period. Furthermore, it can be said that the larger the distance between the couple of heights, the lower the shear exponent obtained. Besides, some extreme shear exponents are achieved. Thus, such cases have been analysed, showing that those values happened at low wind speeds.

The diurnal variation in terms of the time of the day for different couples of heights is shown in figure 6. It is interesting to notice that during the daytime, lower shear exponents are achieved than during nighttime. The shear exponent results, shown in figures 5 and 6, are in line with the results presented by [5] and [17] about the wind shear characteristics.

To illustrate the importance of the wind shear as a whole on the power production, figure 7 shows a wind shear measurement during the 5th of June 2009, and several quite different wind profiles happened that day. In can clearly be seen in figure 7a that in the daytime, when the temperature near the ground is greater than at upper heights due to solar irradiation, the difference between the wind speed is small. Though, during nighttime, the temperature distribution changes sign

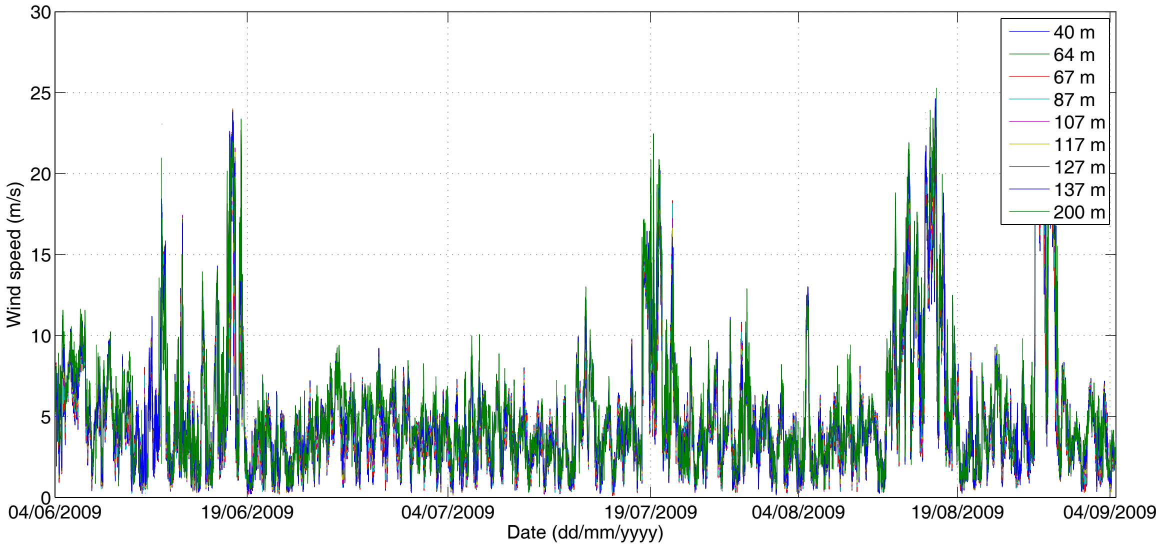


Fig. 4. Wind Speed at WindCube Measurement Heights

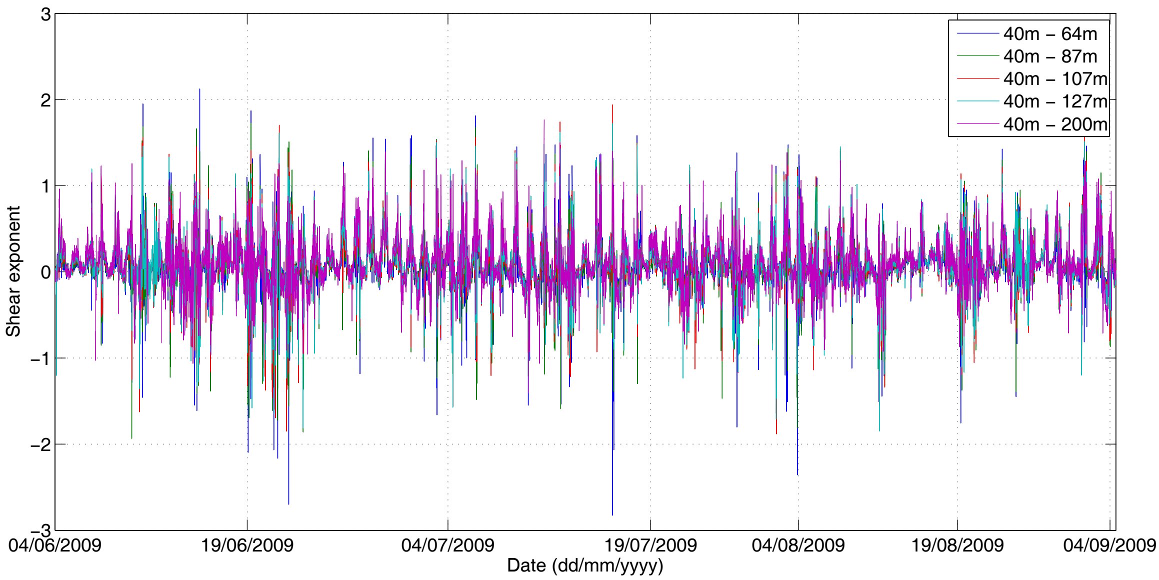


Fig. 5. Shear exponents during measurement period

because of the cooling of the ground, thus producing large wind shear. This effect is called *Thermal Stratification*, [15].

The wind profile situations presented in figure 7b will have different effects on the turbine's power production, and will be discussed in section V.

IV. Equivalent Wind Speed

In previous section I it was stated that one of the most important information on the wind spectra avaliable at a location is its average speed. In simple terms, the average speed (V_m) is given by:

$$V_m = \frac{1}{n} \sum_{i=1}^{n} V_i \tag{3}$$

where V_i is the wind speed recorded at moment i.

Although, in wind power terms, averaging the wind speed using equation (3) is often misleading. Therefore, for wind energy calculations, the wind speed should be weighed for its power content while computing the average, [13]. Thus, the average wind speed is given by:

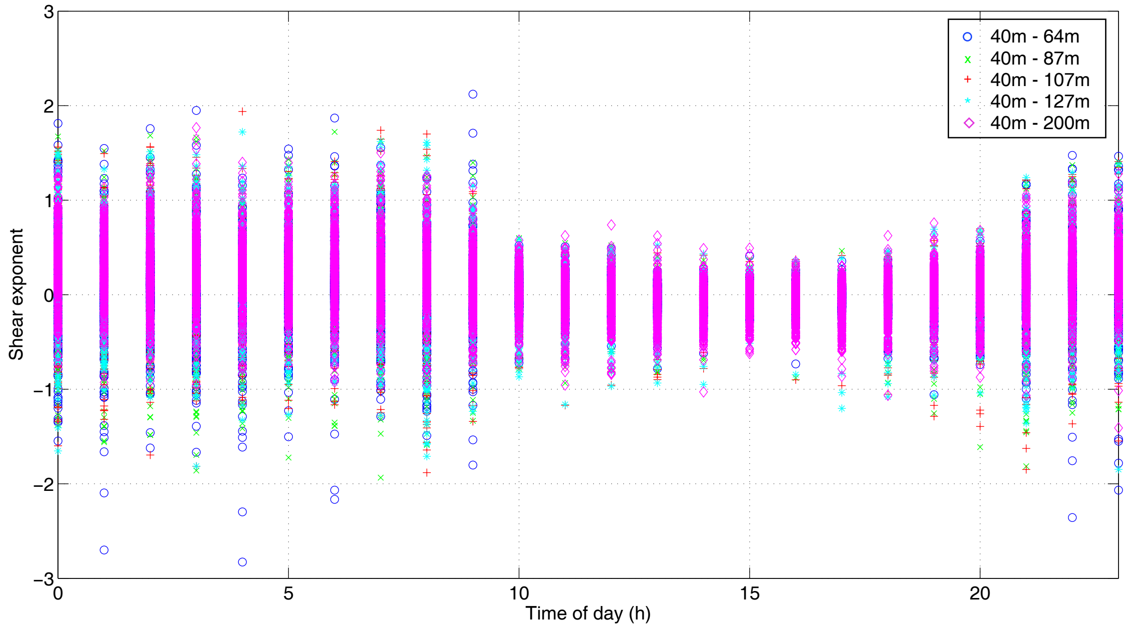


Fig. 6. Shear exponents according to time of day

$$V_m = \left(\frac{1}{n}\sum_{i=1}^{n} V_i^3\right)^{\frac{1}{3}} \qquad (4)$$

Taking previous ideas into account, [3] has developed a new wind speed concept, tested later by [2], [7], which consists of weighing the wind speed recorded at several heights over the rotor swept area according to the area covered by each measurement point. Thus, the equivalent wind speed is given by:

$$V_{eq1} = \frac{1}{A}\sum_{i=1}^{n} \bar{V}_i A_i \qquad (5)$$

where A_i is the area corresponding to the specific data point height and A is the swept rotor area, see figure 8 for details. Besides, if a mixing of eqs. (4) and (5) is performed, the next formula is achieved:

$$V_{eq2} = \left(\frac{1}{A}\sum_{i=1}^{n} \bar{V}_i^3 A_i\right)^{\frac{1}{3}} \qquad (6)$$

In the current approach, due to the asymmetrical layout of the measurement heights for the wind speed selected by the WindCube, measurement points 2, 4 and 5 from figure 8 are calculated using equation (2), whereas measurement points 1 and 3 are real data measured from the WindCube.

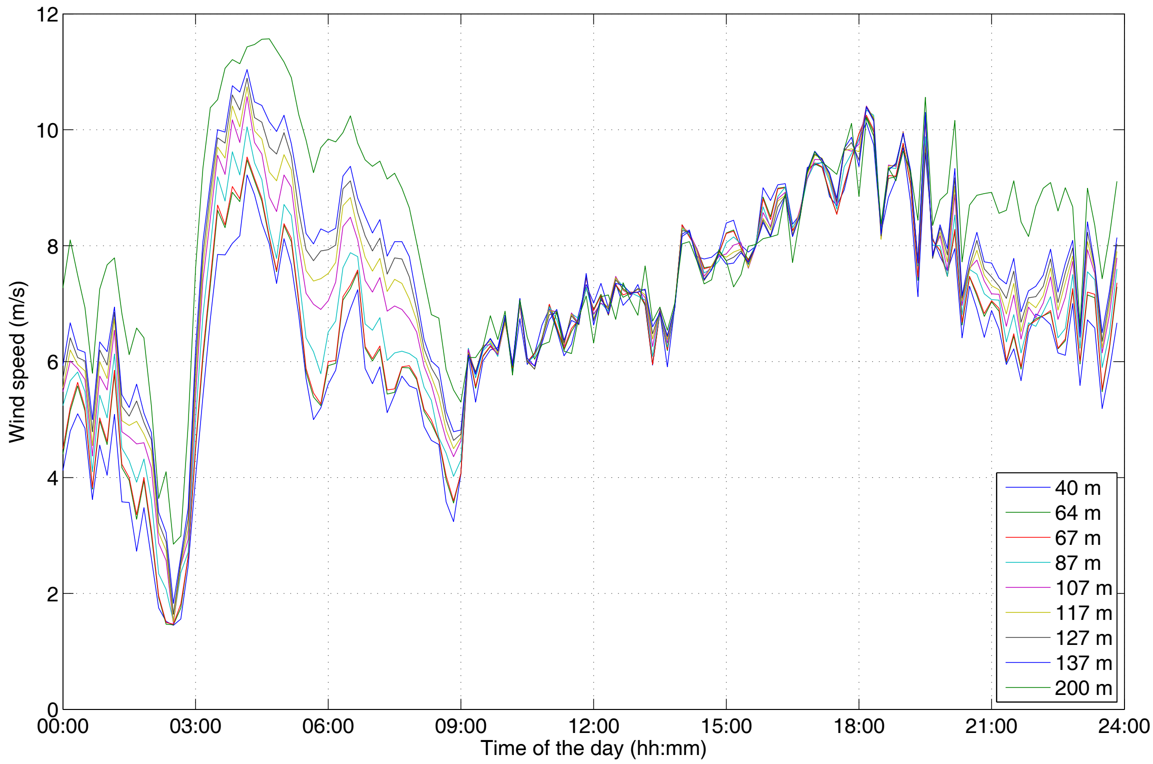
In the present paper, section V discusses the suitability of using the equivalent wind speed calculated using eqs. (5) and (6) instead of the wind speed measured at hub height to improve the power curve perfomance of the wind turbines used, in order to reduce the uncertainty when using the power curve.

V. Power Curve Performance

A measured power curve usually consists of the 10 min mean wind turbine power plotted versus the wind speed at hub height. Such a plot normally shows a significant spread of values and not a uniquely function. Figure 9 shows the power curve measured during the test period taking into account only cup anemometer located at hub height over the meteorological mast. The results that could be achieved using the wind speed measured by the WindCube at hub height are not shown here due to the high correlation degree between both equipment, [11].

Whereas figure 9 shows a spread of values, in [10] is outlined a method called “bin method” for power curve characterization. It consist of taking the mean values of the wind speed and the output power for a period of 10 min. These values are then normalised to a reference air density. Once normalised, the data are grouped using 0.5 m/s bins. Figure 10 shows three different ways to define the power curve. Firstly, the blue line shows the power curve measured taking into account only cup anemometer located at hub height over the meteorological mast. Secondly, the red line shows the power curve measuring wind speed with the WindCube at hub height. And finally, the black lines show both equivalent wind speeds calulated using eqs. (5) and (6).

It can be seen in figure 10 a small variation in the power output, when taking into account the equivalent wind speed calculated both with equation (5) and (6). However a great



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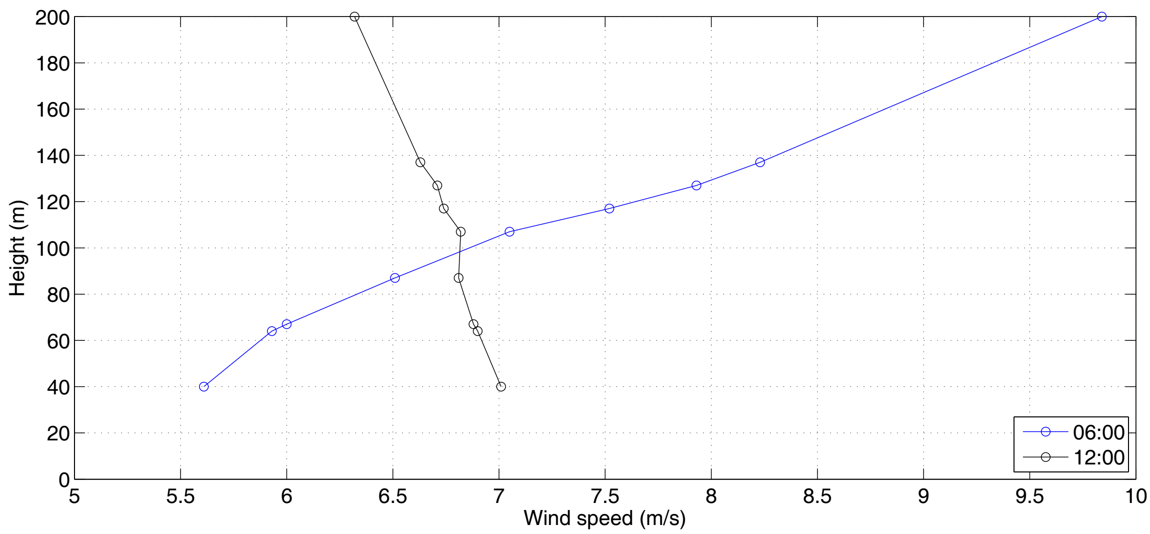

(b)

Fig. 7. Wind Shear During the 5th of June 2009

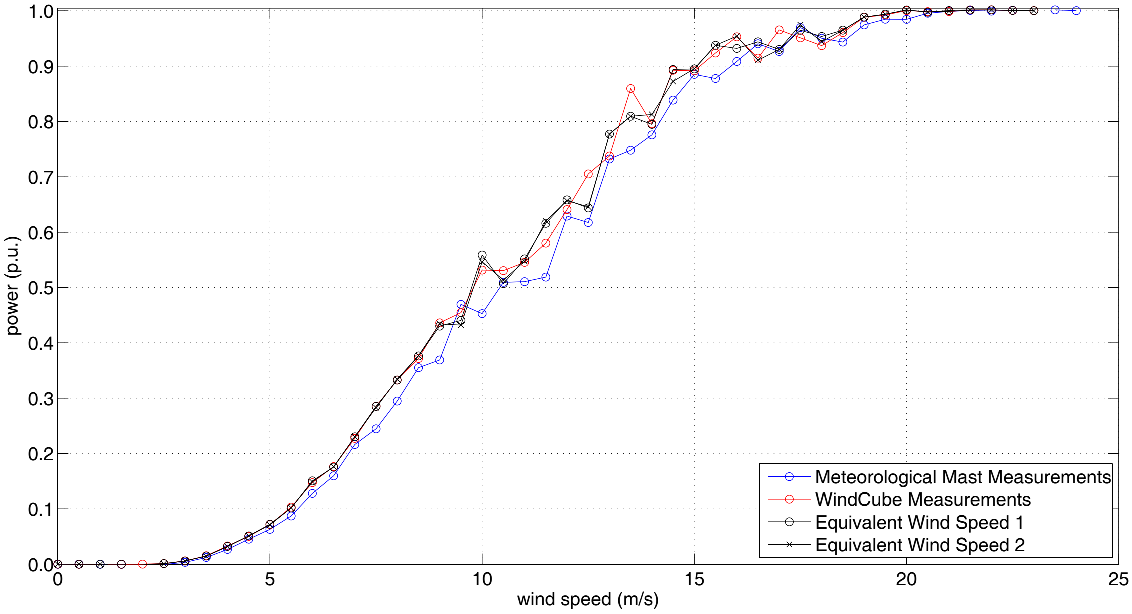

Fig. 10. Power curve according to bin method

variation is observed between using any equivalent wind speed or using the wind speed measured only at hub height.

Besides of studying the suitability of using an equivalent wind speed in power curve characterization, an analysis of the wind shear was performed in section III. Therefore, it is analyzed the behavior of the wind turbine according to the different shear exponents measured during the test period. Thus, figure 11 shows serveral power curve measurements using the bin method when different atmospheric conditions happened.

In figure 11 is proven the high dependence degree between the power produced by a wind turbine and the wind shear measured in front of the wind turbine. It can be noticed that the higher the shear exponent (equal to say "high wind shear" or "noflat wind profile"), the bigger the uncertainty in the power produced, due to the spread of the points. Besides, figure 11 shows that when medium and high shear exponents were found in front of the wind turbine, the power produced by the machine was lower than the expected one for the wind speed measured at hub height

VI. Conclusions

The wind shear over a complex terrain was investigated with the help of a remote sensing equipment. Wind speed was measured at 9 heights at the same time. The wind shear was found to vary considerably each hour, and to deviate both from the logarithmic and the power law profile. On some occasions, wind profiles with a lower wind speed at higher heights were observed.

Even more important, it has been analyzed the influence of wind shear in the power production of a wind turbine. It has been found that when medium and high shear exponents (equal to say "noflat wind profile") were measured in front of the swept rotor area of the wind turbine, the power produced by the machine was lower than the expected one for the wind speed measured at hub height. These initial findings are substantial; however, more work is needed, in order to test a widespread range of wind turbines, to confirm the tendencies observed.

A reduction in the scatter of the power curve measurements seems probable if the wind speed measurement takes place over the whole swept rotor area and is not limited to the measurement of wind speed only at hub height. Remote sensing instruments, such Lidar ones, are able to depict power curve performance characteristics with a higher accuracy degree than instruments based on only one point measurement. In the present work the need for using Lidar instruments has been stated in order to optimize the energy produced by wind turbines, and more specifically when very complex terrains are taken into account, such as the one studied here.

The evolution of remote sensing equipment, has made the wind shear measurements a manageable task. In the near future these instruments could be used to measure the wind shear in front of a wind turbine, and they will probably be used to filter the data for power curve characterization, above all in complex terrain where high shear exponents normally happen.

Therefore, the previous lines underline the need for revising the relevant international measurement standards on power curve.

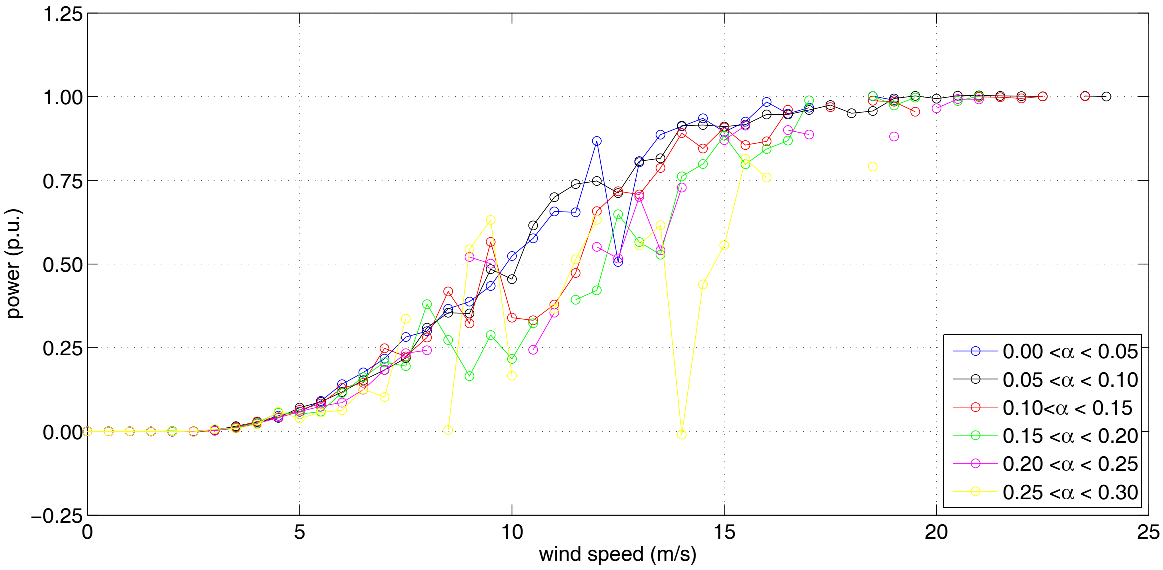

Fig. 11. Power curve related to different shear exponents

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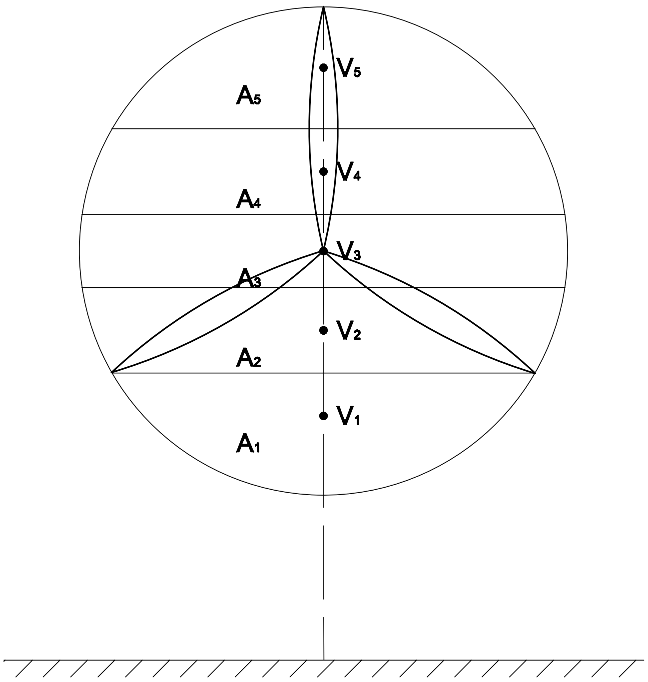

Fig. 8. Swept rotor area divided into 5 horizontal segments

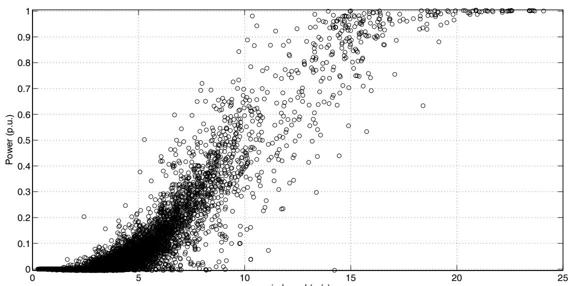

Fig. 9. Power curve measurement during test period