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WAKE EFFECT ANALYSIS OF POWER PRODUCTION AT BEBERIBE WIND FARM

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Abstract. *It is common that one or more wind turbines at a wind farm operate fully or partially in wakes. The wake effect reduces the wind speed and increases the turbulence, affecting the power production of downwind turbines. The Beberibe wind farm is located in the state of Ceará, along the northeast coast of Brazil and it consists of 32 wind turbines of 800 kW, most of which operate under the wake effect. In this paper, a method for the evaluation of the influence of the wind direction on the annual energy production (AEP) of the Beberibe wind farm is proposed, based on data obtained from a meteorological mast and a nacelle anemometer corrected through the nacelle transfer function between the wind speed of the mast and the nacelle anemometer. To analyze the performance of the power production with respect to the wind direction, the nacelle wind speed transfer function as well as one year's data from the meteorological mast and from the wind turbines was obtained based on the IEC 61400-12-2 norm. The results showed that for direction angles greater than 120° most of the wind turbines begin to present power losses of up to 50% of the average production of the farm and the AEP presents a mean difference of 3.9% between the production based on data measured by the mast and the corrected nacelle data.*

Keywords: *Wake effect, power production, Annual energy production, Wind energy*

1. INTRODUCTION

The installed capacity of wind power in Brazil and globally is increasing every year and, therefore, procedures for verifying the energy production of wind farms are required, in order to verify to that the proposed amount is being delivered and evaluate the performance of wind farms. In this context, studies need to be carried out to design new farms, analyze wind patterns, assess factors that influence the production potential and measure the wind farm power output without the installation of a mast, since this is associated with high cost (Albers *et al.*, 1999), attempting to find the best arrangement of wind turbines aimed at preventing the generation of a wake, among other considerations.

One way to solve the "problem" of having only one mast for several wind turbines or not having any masts at the location is to determine the nacelle wind speed transfer function. Studies in this area began in the 1990s in Europe and they showed that the transfer function can be applied to other wind turbines, provided that they have the same characteristics as the test turbine, since the power curves based on the data obtained from the mast are very close to the corrected data measured by the nacelle (Antoniou and Friis Pedersen, 1997); (Albers *et al.*, 1999); (Hunter *et al.*, 2001); (Curvers and Van der Werff, 2008) and (Kim *et al.*, 2013). Albers *et al.* (1999) and Hunter *et al.* (2001), noted that the transfer function can be applied for all wind directions, but it must be based on the undisturbed wind. The annual production of energy based on corrected nacelle data shows a difference of 1% according to Albers *et al.* (1999) and IEC 61400-12, and 1 to 4%, according to Hunter *et al.* (2001) and Smith *et al.* (2002), compared with the data obtained from a tower. Currently, the procedure to obtain the nacelle wind speed transfer function is regulated by the IEC 61400-12-2 norm, which details the requirements and procedures necessary for the determination and application of the function (International Standard, 2013).

The wake effect can occur at a wind farm due to various factors, such as the level of turbulence, terrain features (topography and roughness), wind farm features (layout and distance between wind turbines), wind direction and atmospheric stability (Porté-Agel *et al.*, 2013). The wake generated has two distinct parts: the first is called the near wake, which is the region located just behind the rotor (up to 1 D) and the second is called the far wake, which is the region following the first region. In studies focusing on the influence of the wake effect on wind turbines at wind farms, the wake model, turbulence models and the effects of topography are considered (Vermeer *et al.*, 2003). A reduction in energy production at a wind farm due to the wake effect can vary between 2 and 20% depending on the distance between the wind turbine and ambient turbulence (Jain, 2011).

Since the turbines extract kinetic energy from the wind, further downwind there is a reduction in the wind speed. Thus, the production of a wind turbine that is located behind another decreases (Martínez, 2003). This interaction between wind turbines is important when considering the design of a new wind farm (Jourieh *et al.*, 2009), since a reduction in the wind speed directly affects the energy produced by the wind turbine and consequently the total energy produced by the wind farm. Increased turbulence causes the mechanical dynamic load of the turbine to increase thereby reducing its useful life (González-Longatt *et al.*, 2012); (Jourieh *et al.*, 2009). The recommended distance between wind turbines that are located along the wind direction is of the order of 5 to 10 rotor diameters (D) and the corresponding distance is 2 to 5 D for those located in the perpendicular direction (Martínez, 2003); (Castro, 2003). These distances are recommended because the wind farm efficiency is dependent on the spacing between the turbines (González-Longatt *et al.*, 2012), that is, the power increases as the spacing increases (Jourieh *et al.*, 2009). According to Chu and Chiang (2014), losses of up to 50% can occur due to the wake effect for wind turbines that are aligned and at a distance of less than 12 D.

The wind direction at the wind farm also influences the energy production. It determines the orientation and location of the cones formed in the wake and can thus increase or decrease this effect at the wind farm (González-Longatt *et al.*, 2012), In other words, the efficiency of the wind farm is a function of the wind direction, because for certain directions the wake effect can increase or decrease (Nygaard, 2014). As an example, in one study, a change of 14° in the direction of the wind led to an increase of 43% in the power produced (Porté-Agel *et al.*, 2013). At tightly packed wind farms, the wind direction has a greater influence on the production of the wind farm than the spacing between the turbines (González-Longatt *et al.*, 2012). The annual energy production can suffer losses of 5 to 8% due to wind direction (Sanderse, 2009) and, for a given wind direction, losses in the production due to the wake effect can vary between 30 and 40% (Jafari *et al.*, 2014). IIn the northeastern region of Brazil the prevailing winds are the trade winds, which in the state of Ceará are influenced by the intertropical convergence zone (ITCZ). For this reason, the maximum rainfall occurs between the months of March and April, which is when this zone acts on a regular basis (de Melo *et al.*, 2009). Effects such as El Niño and La Niña also affect the rainfall, causing less or more rain, respectively (Andreoli and Kayano, 2009).

The objective of this study was to analyze the performance of power production with respect to the wind direction and compare the annual energy production based on data obtained from a meteorological mast and corrected values for the data collected using a nacelle anemometer

2. BEBERIBE WIND FARM

The Beberibe Wind Farm (Figure 1), owned by Tractebel Energia and located in Beberibe in the state of Ceará, has been in operation since April 2009. It consists of 32 wind turbines of the type model E-48 (rotor diameter 48 meters and hub height 75 meters), manufactured by Wobben, with a capacity of 800 kW each, giving a total power production of 25.6 MW at the wind farm. The guaranteed capacity factor is 30.9% (Damas, 2013).

As observed in Figure 1, the majority of the wind turbines are located in a line, but there is a region in the upper left corner that has a higher concentration of turbines (total of nine). Therefore, to facilitate an individual study of the wind turbines and verify the behavior of regions in relation to the variables studied, the wind farm was divided into five sectors with an average of six wind turbines each. The geographical distribution of the wind turbines by sector is presented below and also in Figure 1.

- Sector 1: 1, 2, 7 and 10 (front) and 3, 4, 5, 6 and 8 (back)
- Sector 2: 9, 11, 12, 13, 14 and 15
- Sector 3: 16, 17, 18, 19 and 20
- Sector 4: 21, 22, 23, 24, 26 and 27
- Sector 5: 25, 28, 29, 30, 31 and 32

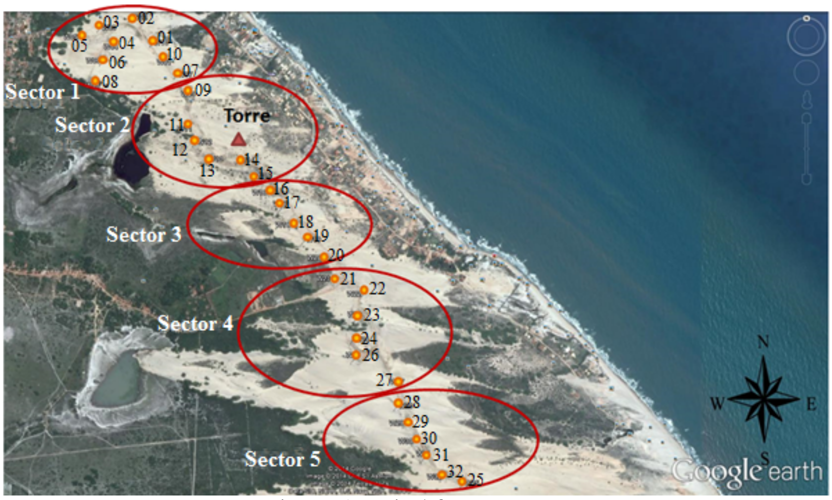

Figure 1: Wind farm sectors

There is a meteorological mast at the wind farm which is 100 meters high and instrumented with a 3D sonic anemometer located at a height of 100 meters and four cup anemometers located at heights of 40, 60, 80 and 98 meters, among other equipment.

3. METHODOLOGY

IIn this section, the methods used to determine the nacelle transfer function for wind speed and to analyze the influence of the wind direction will be described. The data period was from July 1st, 2013 to June 30th,2014.

3.1 Nacelle Function Transfer

The nacelle wind speed transfer function was determined according to the IEC 61400-12-2 norm, which describes the measurement of the electrical performance of a wind turbine based on the speed data measured by the nacelle. The steps used to determine the function were: select the closest distance for the 2 D wind turbine; find the undisturbed section of the tower and wind turbine; create a valid database for the function and the wind farm; divide the speeds of the tower and the nacelle into bins; create a chart with V_{nacelle} x V_{mast}, with the assistance of the functions, determinin V_{free} according to equation D1 of IEC 61400-12-2; obtain the power curves from the corrected nacelle data and the mast data; choose the function that best fits the data obtained from the mast.

Wind turbine 14 was used to determine the nacelle transfer function for the wind speed, because this is located at a distance of 2.6 D from the mast. The procedures described above were followed and tests were performed using linear, cubic and fourth-order polynomial functions. The function selected was determined based on the V_{nacelle} x V_{mast}, the power curve (Figure 2) and statistical data (Table 1).

3.2 Influence of the wind direction

To determine the influence of the wind direction on the wind speed and the production of the wind farm, the wind direction was divided into sectors with a width of 10°, and through the methods of bins, the speed and the average production for each bin were calculated. The ratios for the speeds (that is, the wind speed of each wind turbine and the average wind speed at the wind farm) and the powers (that is, the average power of each wind turbine and the average power at the wind farm) were then determined. The speed used in the speed ratio calculation was measured by the nacelle and corrected using the transfer function.

4. RESULTS AND DISCUSSION

The results obtained for the transfer function and the wind direction are reported in this section.

4.1 Nacelle Function Transfer

In Figure 2a, it can be seen that the data measured by the nacelle and the tower have a good correlation with R^2=0.9846. When applying the functions to the average bins (Figure 2b),it is clear that the linear function is not well suited to the endpoints of the graph, while the cubic and fourth-order functions showed better behavior. As shown in Figure 2c, between speeds 7 and 9 m/s practically all functions have the same result and thus none of the curves can be distinguished while between 9 m/s and 11 m/s the linear functions and V_{free} are above the mast curve. From 11.5 m/s the mast has a value lower than all functions of the curve and at the end it becomes higher. The maximum difference found between the bins for the power curves of the tower and of the nacelle wind speed corrected by the fourth-order function was 14.74 kW, representing 1.84% of the rated power of the wind turbine. This also represents the maximum difference found for the cubic function, but for the linear function and the function V_{free}, this difference increased to 44.06 kW and 29.75 kW, respectively.

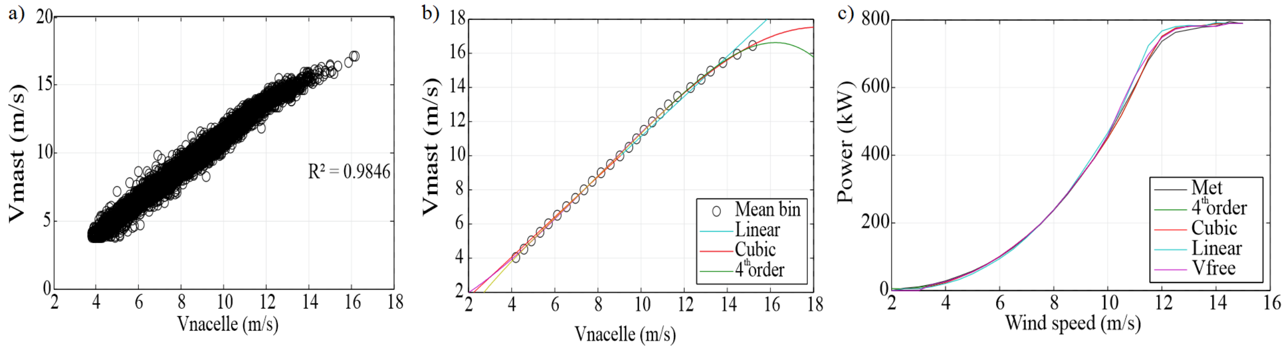

Figure 2: Results for the nacelle transfer function

Table 1 shows a comparison between the results obtained for each of the functions tested.

Table 1: Results for the different functions

Variables	**Linear**	**Cubic**	**4th order**	V_{free}
Average speed (m/s)	8.5014	8.5312	8.5221	8.554
Difference average speed (%)	-0.28	0.07	-0.04	0.35
R^2	0.9960	0.9996	0.9997	0.9992
SSE	1.4461	0.1321	0.1011	0.2747
Mean error (%)	0.4828	-0.3694	0.0566	0.4376
Average difference of power curve (kW)	9.7237	4.6272	4.2374	5.7039

According to Table 1 and Figure 2 the fourth-order polynomial function was the function which provided results closest to the tower performance data with the R^2 value closest to 1, the sum of squares due to error (SSE) closest to 0, the smallest average error in each interval and the smallest difference in the power curve compared with the other functions. Thus, in this study the fourth-order polynomial function (Equation 1) was applied as the nacelle transfer function for wind speed at the Beberibe wind farm.

$$y = -0.0005784x^4 + 0.01825x^3 - 0.2101x^2 + 2.283x - 2.989 \quad (1)$$

4.2 Influence of the wind direction

Figure 3 shows the wind speed and its corresponding direction frequency diagrams for the Beberibe wind farm. The prevailing wind direction is between 60° and 120°, which concentrate 84.14% of the data. In relation to wind speed, the greatest incidence lies between 8 and 9.5 m/s.

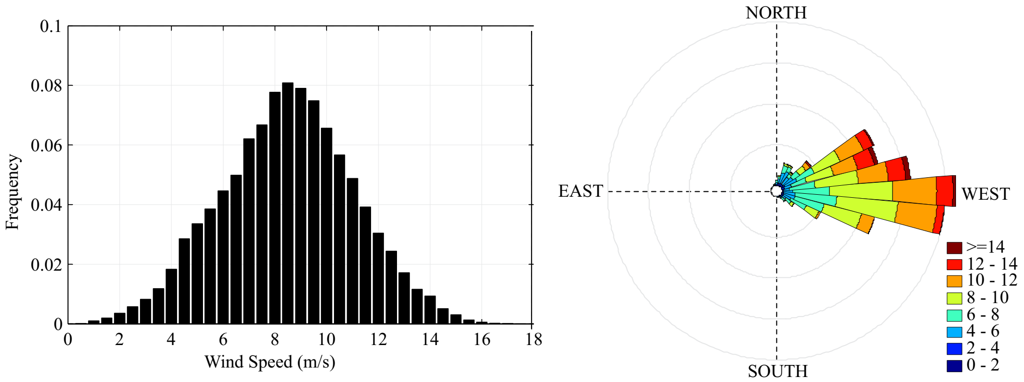

Figure 3: Analysis of wind speed

Figure 4shows simulations in Matlab for the wind directions 60°, 80°, 100° and 120° as a function of the diameters and speeds of the wake generated by each turbine. With respect to wind speed, this was not taken into account when the wind turbine was influenced by its neighbors, because only the length of the wake was of interest Figures 5-9 show the speed and power ratios for the sectors/ turbines.

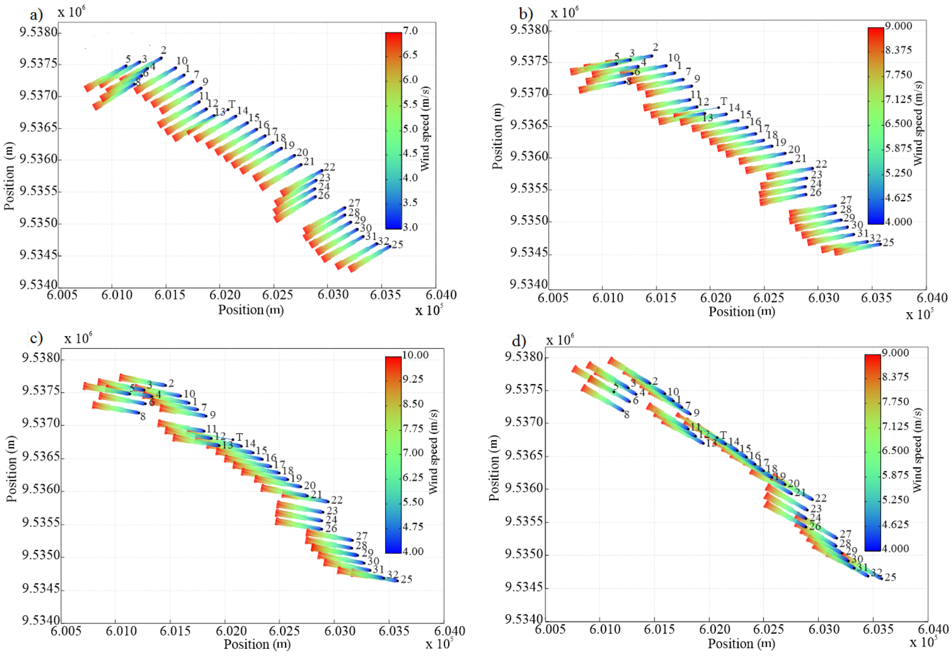

Figure 4: Wake simulations based into the wind direction: a)$\theta = 60°$ b)$\theta = 80°$ c)$\theta = 100°$ d)$\theta = 120°$

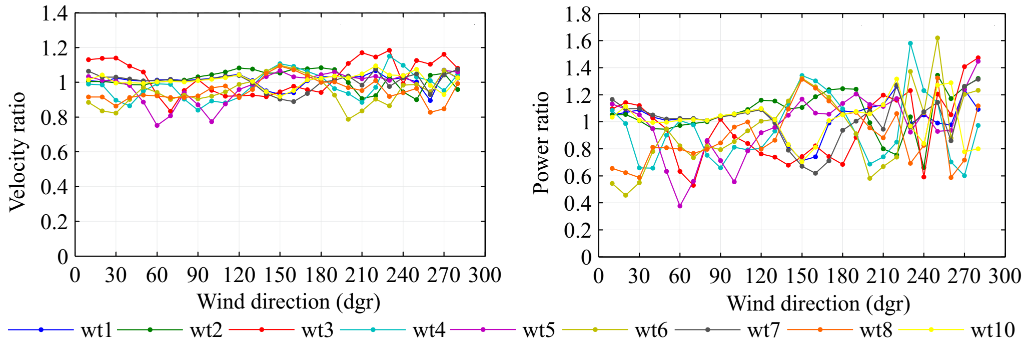

Figure 5: Speed and power ratios for sector 1

Figure 5 reports the wind speed and power ratios for sector 1, where the greatest difference is observed in terms of the behavior of the wind speed at the wind turbines, particularly for the turbines located at the back (wt3-wt6 and wt8), since these are subject to wakes created by the presence of the front turbines, as shown 4. This results in lower wind speeds compared with the other turbines and, therefore, these do not follow the overall behavior of the wind farm, with several power outages for the angular sector between 60° and 120°. On analyzing only the front wind turbines (wt1, wt2, wt7 and wt10), it can be observed that they remain in the middle of the wind farm speeds for an angle of 120°, when turbines wt1, wt7 and wt10 show a slight decrease in the wind speed, and average values return at an angle of 170° for wind turbines wt1, wt2 and wt10 and 185° for wt7. It was also observed that between the angles 130° and 170° tthe downwind turbines (wt3-wt6 and wt8) have a greater speed ratio than the front turbines, as can be seen in Figure 4d, and at 120° tthe front turbines are subject to wakes from one another. On analyzing the power ratio, it is clear that for a downwind turbine the production with a direction of 130° is mostly below the wind farm average. However, from the direction of 130° there is an inversion in the powers.

Figure 6 shows the results for sector 2 where we can note that turbine wt13 shows a decrease in the speed for a direction of 90°, due to the fact that in this position the wind arrives at turbine wt14 before turbine wt13 and the distance between them is 4.2 D. For directions between 170° and 190° turbine 9, which had shown good wind speeds, shows a fall compared to the other wind turbines of the sector since it lies between the wakes of wind turbines wt11-15 and the mast. Since the turbines of sector 2 are closest to the mast, with the smallest distance being 2.6 D (wt14) and the largest 5.8 D (wt11), depending on the wind direction, these will also be affected by the tower wake. The strongest influence of

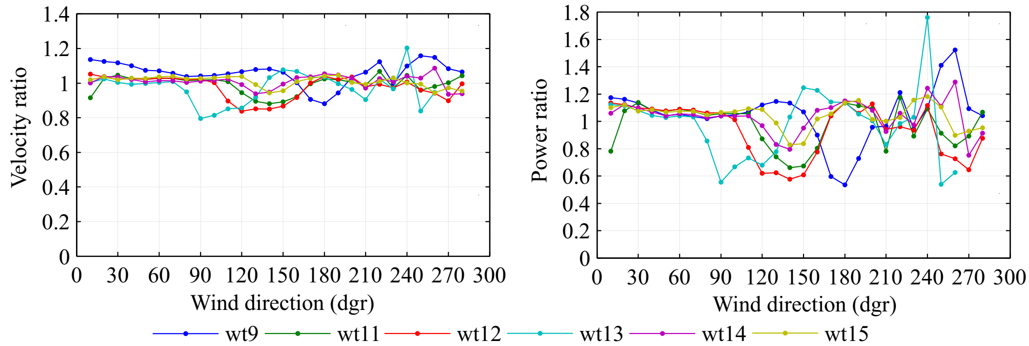

Figure 6: Speed and power ratios for sector 2

the wake in this area is between 110° and 160°, when the wind turbines closest to the mast have lower speed and power ratios, as can be seen in Figure 4, and as the wind changes direction turbines wt14 and wt15 become affected by the wakes of the turbines in the sector 3, and turbines wt11-13 are subjected to their own wakes.

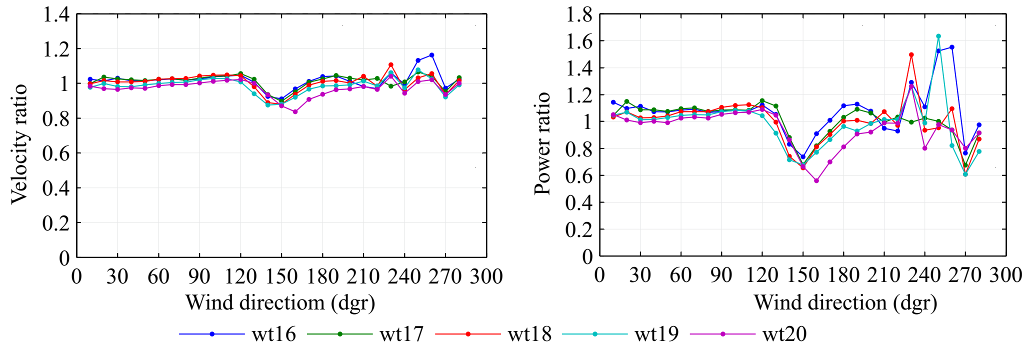

Figure 7: Speed and power ratios for sector 3

Figure 7 shows the results for sector 3. This sector shows greater uniformity in terms of speed and power, although there is a decrease in the speed and power ratios for directions between 120° and 160°, returning to the average of the wind farm shortly after this angle. This decrease is due to the wake caused by the wind turbines of the sector and turbines wt21 and wt22, as shown in Figure 4d. With this fall the sector loses 40% of production. There is a further decline in the power ratio for directions between the angles of 260° and 280°, reaching a decline in the production of 40%.

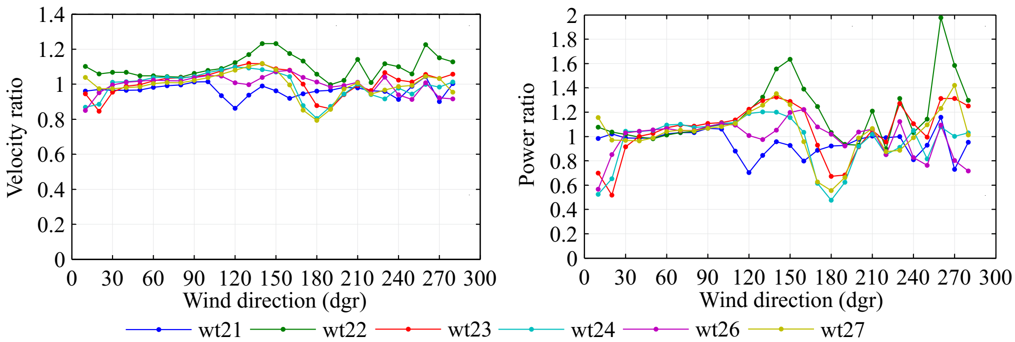

Figure 8: Speed and power ratios for sector 4

Figure 8 sshows the results for sector 4, for directions between the angles of 100° and 160°. The wind turbines wt21 and wt26 have a lower speed compared to the others, because, as noted in Figures 4c e d, they work partially or completely in the wake of wind turbines wt22 and wt27, resulting in lower power. For directions between 150° and 160° turbine wt21 lies in the wake of wind turbine wt24 and the lowest power is observed for this direction. Even though the distance between them is 8.4 D, for angles between 30° and 110° all of the wind turbines show the same behavior. Except for wind turbine wt21, which lies in a wake for directions 100° and 110°, at directions up to 100° the turbines do not lie in a wake, and at 110°, all of them start working partially. The influence of the wakes in this sector is observed from 170°, when four wind turbines of this sector begin to produce power at levels below the average of the wind farm. Wind turbines wt24 and wt27 are those which show the greatest loss when all turbines lie in the wake of this sector, reaching 55% and 45%, respectively. It should be noted that this sector has a production well above the average of the wind farm, reaching in some cases 50% above the average.

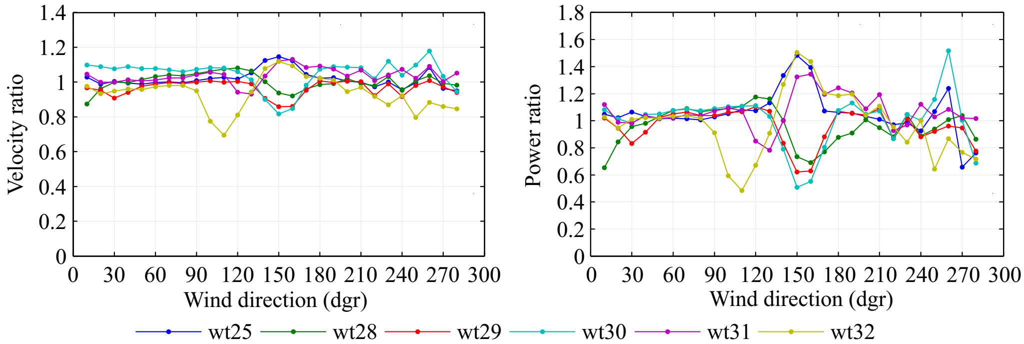

Figure 9: Speed and power ratios for sector 5

Figure 9 shows the results for sector 5, in which the turbine wt32 shows a significant decrease in speed and power for directions between 90° and 110°, as this lies in the wake of wind turbine wt25, since the distance between them is 2.7 D (Figure 4). The decrease was 50% of the power produced for this wind turbine. When the wind direction is between 150° and 160°, turbines wt28-30, which are located more to the left of this sector, lie within the wake of wind turbine wt31, since these four wind turbines are almost in a straight line. Being located only 2.5 D away from turbine wt31, wt30 is the turbine with the lowest power, followed by wt29 (distant 5.2 D) and then 28 (7.8 D), indicating that the wake effect diminishes with distance. With the exception of wind turbine wt32, all have an average speed equal to the wind farm speed up to an angle of 120°, after which there is an inversion in the ratios, that is, wind turbines that had the lowest average (wt25, wt31, and wt32) now have a higher average than others (wt28-wt30). This is because turbines wt25, wt31 and wt32 receive the wind from the front, without obstacles, while the other wind turbines are in the wake of wt31. During this inversion, the turbines produce much more than the average power of the wind farm, reaching 50% above that produced by the other wind turbines.

4.3 Annual Energy Production

Figure 10shows the annual energy production (AEP). The AEP based on the corrected nacelle data compared with that based on the production according to the mast data presents a maximum difference for the turbines of 7.5% and for the wind farm of 3.93%. This difference can be explained by the fact that the mast, for certain wind directions, lies in the wake of neighboring turbines and thus the wind speed measured is lower than that arriving at the turbines. It is also observed that, for turbines wt4-6 and wt8, the difference was higher than that found by Hunter *et al.* (2001). This is because these wind turbines work in the wake most of the time and, therefore, have a slower rate than the average of the wind farm. For a low annual average, the difference in the AEP values can reach 12% (Hunter *et al.*, 2001).

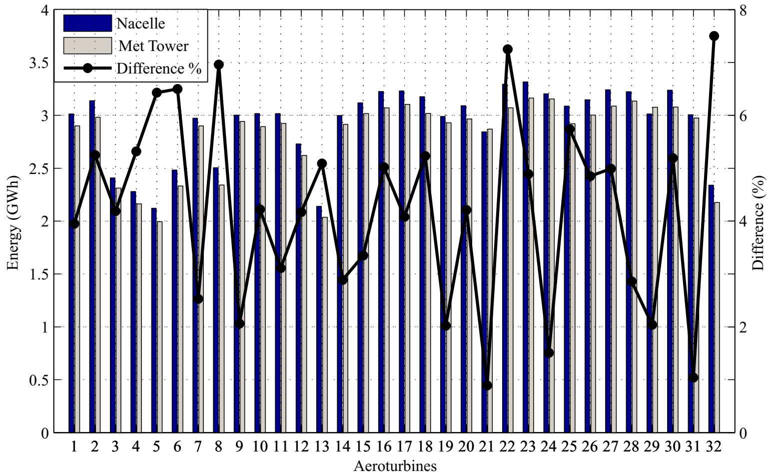

Figure 10: AEP Nacelle x AEP Met Tower

5. CONCLUSION

The results of this study clearly demonstrate that the wind direction influences the production of wind turbines and hence the wind farm production. At around 120°, virtually all wind turbines of the wind farm are subjected to the wake effect. The turbines situated at the back of the first sector (wt3-wt6 and wt8), being in the most part at the front of the wake of the other wind turbines, show the worst results for speed, power and annual energy production. On comparing the energy production of the wind farm, based on the corrected nacelle data and the mast data, the difference is less than 5%, suggesting that it is possible to expand a transfer function for one wind turbine to the entire wind farm.

6. ACKNOWLEDGEMENTS

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