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ANALYSIS OF THE WAKE EFFECT IN AIRCRAFT ON THE PRODUCTION OF POWER IN MACAU WIND

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Abstract: *Over time the investments directed to the generation of wind energy are growing all over the world, with that, it is necessary to analyze the phenomena that cause the reduction in the energy production of a wind farm. One of them is the effect of the treadmill that entails a significant decrease in wind speed. In addition, there is a high investment related to an anemometric tower that could be avoided if a function was used that related the speed of the wind in the tower and the aerogenerator. Thus, the purpose of this work is to evaluate the wake effect on the energy production of the Macau mill and to determine if a transfer function could relate the wind speed in the tower and the turbine. By means of two algorithms the necessary distance was verified so that the wind power plant does not present losses in the productivity and if the function of transfer of the norm IEC 61400-12-2 would relate the measured data in the tower and the aerogenerator with precision. The results show that the ideal distance between wind turbines for a plant implemented in Macau should be 800 m and that it is possible to estimate the power of a wind turbine by means of the transfer function.*

Keywords: *Wind energy, wake effect, annual energy production.*

1. INTRODUCTION

With increasing world population and industries there is a need for new, low-cost sources of energy and, above all, that do not pollute the environment. Thus, renewable energy sources (wind power, solar energy, small hydroelectric and biomass power plants) show an average annual growth of 10% in energy generation (Sá, 2015). Given this, wind energy in Brazil has stood out over the years with a total power of around *282* MW contracted in 2012 and *1505* MW in 2013 (ENERGÉTICA, 2013).

This growing demand for wind resources implies the indispensability of evaluations of wind farms generating potential, since they are requirements in contracts between manufacturers, financiers and developers of wind farms (Albers; Klug; Westermann, 1999).

These factors stimulated the study of the effect of the treadmill on the energy production of a Macau wind farm, by collecting wind speed data measured in an anemometer tower and the anemometer located in the nacelle (part of the wind generator where the generator is located). From this data an analysis of the wind speed, annual energy production, capacity factor (ratio between the actual generation of the plant and the total capacity, both in the same period of time) and the power curves of the wind turbines were carried out, Which are the graphs of the power generated by the wind turbine as a function of the speed of the wind that affects the blades.

The treadmill is a phenomenon that results in the reduction of wind speed in a certain region after the wind hits the blades of a wind turbine. The formation of vortices in the belt region causes a decrease in the wind velocity in a given location. The main objective of this work is:

- To analyze the influence of the effect of the treadmill on aerogenerators on the power production of a power plant in Macau by means of wind data measured in the nacele of the aerogenerator;

The specific objectives are listed below:

- Study the impact of the treadmill on the neighboring wind turbines;
- Determine the distance between wind turbines that minimizes the effects of the belt in the production of energy from the wind farm;
- The impact on the annual production of the park;
- Evaluate whether a transfer function allows the power curve to be constructed effectively.

2. THEORETICAL FOUNDATION

2.1. The Weibull Distribution

When it is desired to find precise estimates of wind power it is of fundamental importance to know the characteristics of the wind of a region. The Weibull distribution is used to show the wind speed distribution in a given period of time (Catalão, 2012). It is divided into: probability density function, dependent on the factors *k* (form factor representing the velocity distribution) and *c* (scale factor that characterizes the distribution), and cumulative distribution function that is used when evaluating the fraction the turbine of the wind turbine is in rotation (Stankovic; Campbell; Harries, 2009).

This distribution reliably represents the hourly average wind speed variation for the period of one year, $f(v)$, in several places (Burton *et al*., 2000). Its formula is given by Eq. (1):

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

Where k is the form factor, dimensionless, c is the scaling factor in m/s and V is the mean wind speed (m/s). According to Araújo (1989), the shape factor can be determined by means of the standard deviation (σ) And the average speed ($\bar{V}$) Measured in a region, according to Eq. (2).

$$k = \left(\frac{\sigma}{\bar{V}} \right)^{-1,086} \quad (2)$$

Thus, from the value of k, it is possible to find the value of the scaling factor using Eq. (3), where the gamma function, $\Gamma(1 + (1/\text{k}))$, can be determined by means of Table 1 which presents several values for gamma as a function of the value of k (Rohatgi,1994).

$$c = \frac{\bar{V}}{\Gamma(1+(1/k))} \quad (3)$$

Table 1 - Range values for some Weibul shape factors

k	$\Gamma\left(1+(1/k)\right)=\bar{V}/c$
2,3	0,885915
2,4	0,886482
2,5	0,887264
3,0	0,892979
3,5	0,899747
4,0	0,906402

Source: Rohatgi (1994)

2.2. Power Curve

The relationship between the output power of a wind turbine and the wind velocity incident on it generates the power curve (Hau, 2005). It is calculated by means of the power coefficient (c_p) Multiplied by the energy that the wind provides at the height of the rotor axis, according to Eq. (4).

$$P_M= c_p P= \frac{1}{2} c_p\, \rho\, A_r V_0^{\,3} \quad (4)$$

Where, P_M Is the maximum power drawn from the wind turbine (Watts), P the available wind power (Watts), c_P Is the power coefficient (dimensionless), ρ Is density of air, A_r Is the area of the rotor (area of the circumference formed by the movement of the wind turbine blades)e V_0 it's the wind speed. It can be seen from Eq. (4) that the power curve is dependent on atmospheric pressure, because ρ and V_0 undergo changes due to altitude (Ackermann, 2012).

2.3 Annual Energy Production (AEP)

Thus, the *AEP* is measured according to Eq. (5), where *8760* is the number of hours in a year and *f(v)* is the velocity distribution of the region in the studied period.

$$\text{AEP} = 8760 \int_{V_{in}}^{V_{out}} f(v) P dv \tag{5}$$

Figure 1 shows the formation of the resulting energy distribution curve from the Weibull power and distribution curves of a wind turbine. Consequently, the area of the energy distribution curve results in the energy generated in the period of one year. These results are superior in relation to the real, since the states of operation of the turbine are not considered.

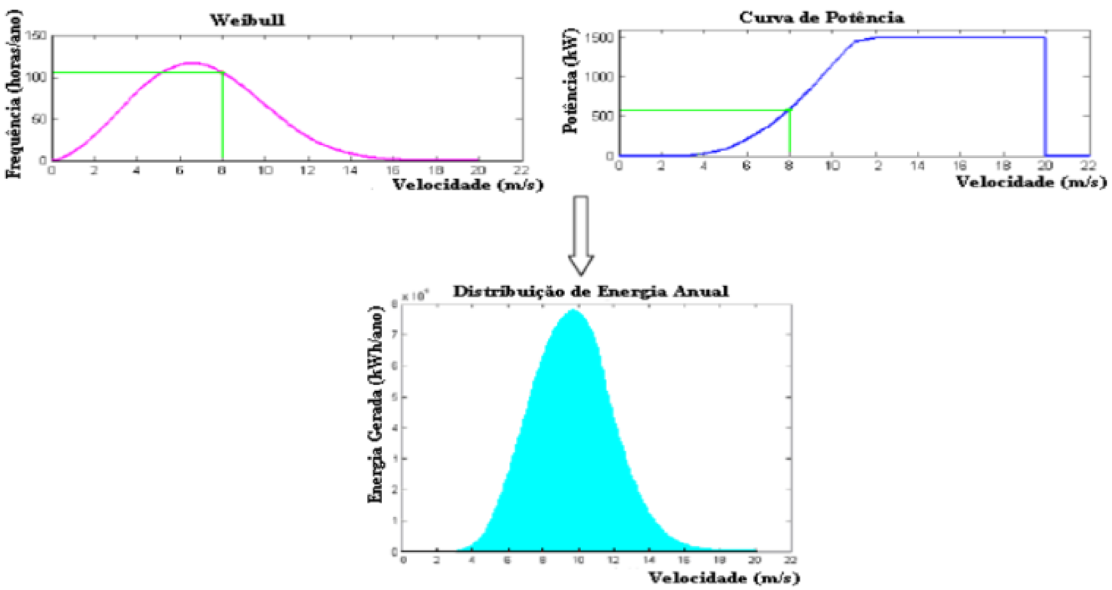

Figure 1 - Construction of the annual energy distribution curve
Source: Mendonça (2009)

3. Treadmill Effect

There are four treadmill situations: when the wind turbine is located entirely in the treadmill region; In the situation where she is almost completely on the treadmill; Wind turbine partially in the belt region; And outside the treadmill region (González-Longatt; Wall; Terzija, 2012).

It is titled near wake the treadmill region just behind the rotor (up to *1 D*), where the rotor characteristics influence the region. There is great interest on the part of researchers in ascertaining the physical processes of energy extraction from near wake. The far wake region is soon after the near wake, the studies of this region prioritize to verify the influence of the wind turbine in the energy production analyzing the model of the treadmill, type of turbulence and the effect of the terrain (Vermeer; Sørensen; Crespo, 2003). Therefore, in order to minimize losses, it is fundamental to carry out an analysis of the distance between wind turbines, turbulence, wind direction and the arrangement of wind turbines in the plant (Martínez, 2003), (González-Longatt; Wall; Terzija, 2012) e (Jain, 2011).

3.1 Jesen Model

The Jensen model is based on the idea that the expansion of the belt diameter is linear and changes according to the distance at the back of the wind turbine, according to Fig. 2.

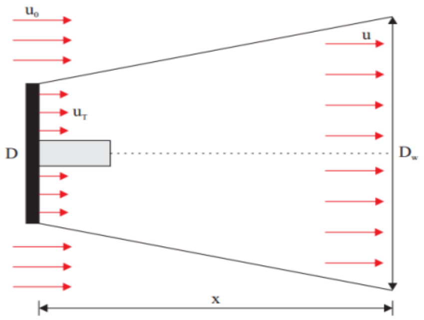

Figura 2 - Perfil de esteira segundo o modelo de Jesen
Fonte: Choi e Shan (2013)

The diameter of the belt (D_w) is calculated as a function of the diameter of the rotor (D), of the decay coefficient of the mat (k_w) and distance (x) behind the aerogenerator where it is desired to calculate the diameter of the conveyor. The variable h is the height of the turbine hub and z_0 is the average surface roughness of the wind turbine. With this, Eq. (6) shows how the D_w.

$$D_w = D(1+2k_w s) \tag{6}$$

$$s = \frac{x}{D} \tag{7}$$

$$k_w = \frac{0,5}{\ln\left(\frac{h}{z_0}\right)} \tag{8}$$

The velocity of the wind in a belt can be calculated according to Eq. (9), where c_T is the coefficient of buoyancy and is equivalent to about *0.8888*.

$$u = u_0\left[1-\frac{\left(1-\sqrt{1-c_T}\right)}{\left(1+\frac{k_w x}{r_0}\right)^2}\right] \tag{9}$$

4. METHODOLOGY

The present work consists of analyzing wind speed data collected at a wind farm in Macau, RN, and investigating the influence of each windmill conveyor on the total power produced at the wind farm. The data are from the anemometer located in the nacelle of the turbine 1 and were collected in the period of one year between January 1, 2005 and December 31, 2005, in order to study the annual energy production. For the calculation of the Weibull parameters, we used Eq. (2), Eq. (3) and Table 1. Table 2 shows the values of the form factor (k) and scale factor (c) found for each Turbine in situations where *10D*, *15D*, *20D* and *30D* are spaced apart, where *D* is the rotor diameter of the wind turbine.

Table 2 - Form (k) and scale (c) data of each turbine

Distance 400 m (10D)	***k***	***c* (m/s)**	**Distance 600 m (15D)**	***k***	***c* (m/s)**
Turbine 1	3,0378	7,8876	Turbine 1	3,0378	7,8876
Turbine 2	3,0378	6,3353	Turbine 2	3,0378	6,8588
Turbine 3	3,0378	5,0885	Turbine 3	3,0378	5,9642
-	-	-	Turbine 4	3,0378	5,1863
-	-	-	Turbine 5	3,0378	4,5098
Distance 800 m (20D)	***k***	***c* (m/s)**	**Distance 1200 m (30D)**	***k***	***c* (m/s)**
Turbine 1	3,0378	7,8876	Turbine 1	3,0378	7,8876
Turbine 2	3,0378	7,1556	Turbine 2	3,0378	7,4635
Turbine 3	3,0378	6,4916	Turbine 3	3,0378	7,0623
Turbine 4	3,0378	5,8891	-	-	-

Thus, the algorithm constructed to create the Weibull and power curves, through the equations mentioned above, multiplied the power by the annual frequency and created the curve of the annual energy production for each wind turbine in different spacing situations. It was analyzed the distance required for the wind power plant to have no losses in the annual energy production related to the treadmill effect.

After this step, a transfer function was used that associates the data of wind speed in the nacele with those of an anemometric tower, because if there is no need to implement it to verify the power curve of a wind turbine a high connected cost It can be avoided by promoting significant savings in the construction of a wind power plant that occupies a very large area and needs to install more than one wind speed measurement tower.

However, for the creation of the transfer function, speed data from the nacele and an anemometric tower are essential. In this step, the results were not real due to the lack of wind speed data in an anemometric tower at the Macau mill, Because the company did not provide data. Thus, data from the anemometric tower of the Camocim Park in Ceará were used to determine if the transfer function allows the creation of power curve graphs within an acceptable margin of error and to confirm if the elaborated algorithm works correctly. Thus, a second algorithm was created and built the speed graph of the nacele by tower speed. Thus, the next procedure was to find the wind velocity incident on the wind turbine nacele (V_{free}) by means of the equation *D1* of the standard IEC 61400-12-2, which is being shown in Eq. (10). Where V_{free} is the wind speed measured in the nacelle (corrected by the nacelle's transfer function), $V_{torr,1}$ and $V_{torr,i+1}$ are the average speeds measured in the tower at i and $i+1$, respectively, and $V_{nac,i}$ and $V_{nac,i+1}$ Are the average speeds in the intervals i and $i+1$, respectively.

$$V_{free}=\frac{(V_{tor,i+1}-V_{tor,i})}{(V_{nac,i+1}-V_{nac,i})}\left(V_{nac}-V_{nac,i}\right)+V_{tor,i} \tag{10}$$

Finally, the power curve was plotted with the wind speed data measured in the anemometric tower and using the corrected velocity data, in order to compare the results obtained.

5. RESULTS AND DISCUSSIONS

With the average wind speed data measured in the wind generator's nacele and the data provided by the manufacturer it was possible to generate the power curve plots and study the final results. Fig. 3 shows the curves of the manufacturer and the three turbines in the same graph, where the red curve is obtained from the data provided by the manufacturer, yellow refers to turbine 1, green is relevant to turbine 2 and curve Blue curve was obtained with data from the anemometer of the nacelle of the turbine 3. It is possible to verify that the turbine 3 (blue curve) presented the greatest dispersion of results, in relation to the three turbines, in comparison to the manufacturer (red curve).

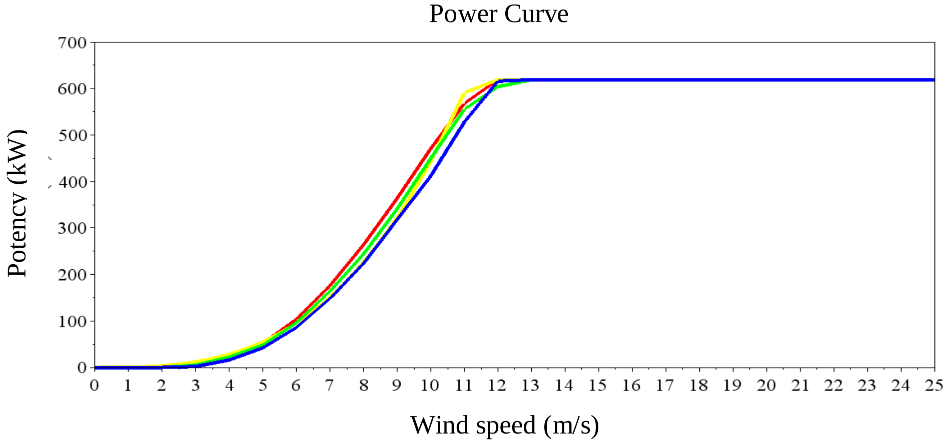

Figure 3 - Power curve of the 3 turbines and the manufacturer

It was investigated what would be the adequate distance so that the treadmill effect does not decrease the energy production of the plant and deduce the best arrangement of the wind turbines in the park. The curve of Fig. 4 indicates the percentage of wind speed decrease that affects a windmill associated to the wake effect, when one wind generator is located at a certain distance from another. The graph of Fig. 5 shows the diameter of the mat formed for each spacing between wind turbines. Thus, as the distance between the wind turbines increases the percentage decrease in speed decreases and the diameter of the conveyor increases.

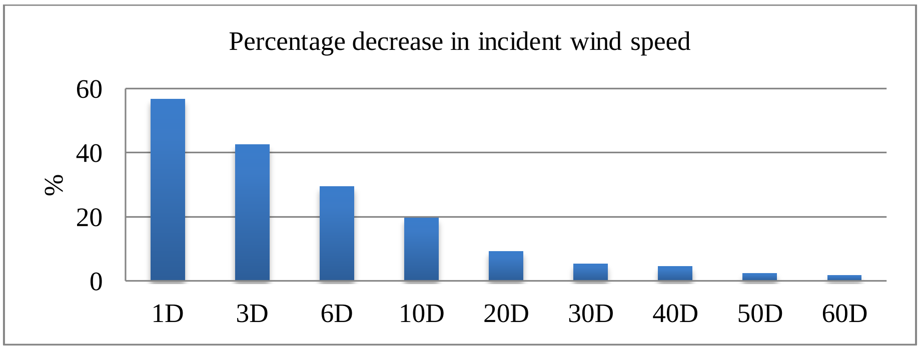

Figure 4 - Percent speed reduction chart for turbines at different spacings

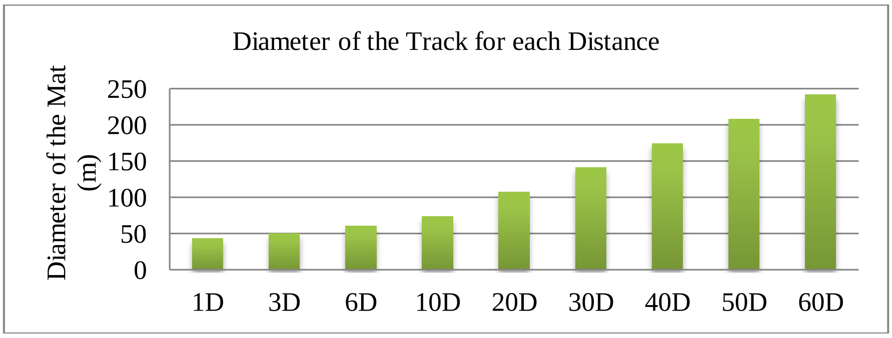

Figure 5 - Graph of the diameter of the belt for turbines in different spacings

Although the diameter of the conveyor belt is larger, which implies that the windmill area under the treadmill is increasing, the percentage of speed decrease is very low, as is the case for a *60D* spacing where the wind speed reduces 1,*825%* And the diameter of the mat would be *241.74* m. Therefore, an analysis was made to verify the distance between aerogenerators that would minimize the losses of energy production due to the wake effect.

Figure 6 shows the power of the park that would be obtained as a function of the distance between the wind turbines, considering the same region of *60D* (*2400* m) for their installation. Thus, a smaller distance between wind turbines considerably decreases the production of the park and as the distance increases from *50D* (*2000* m) the power becomes constant. Therefore, the recommended distance for the positioning of Macau wind turbines in order to produce as much power as possible in the plant should be *20D* (*800* m).

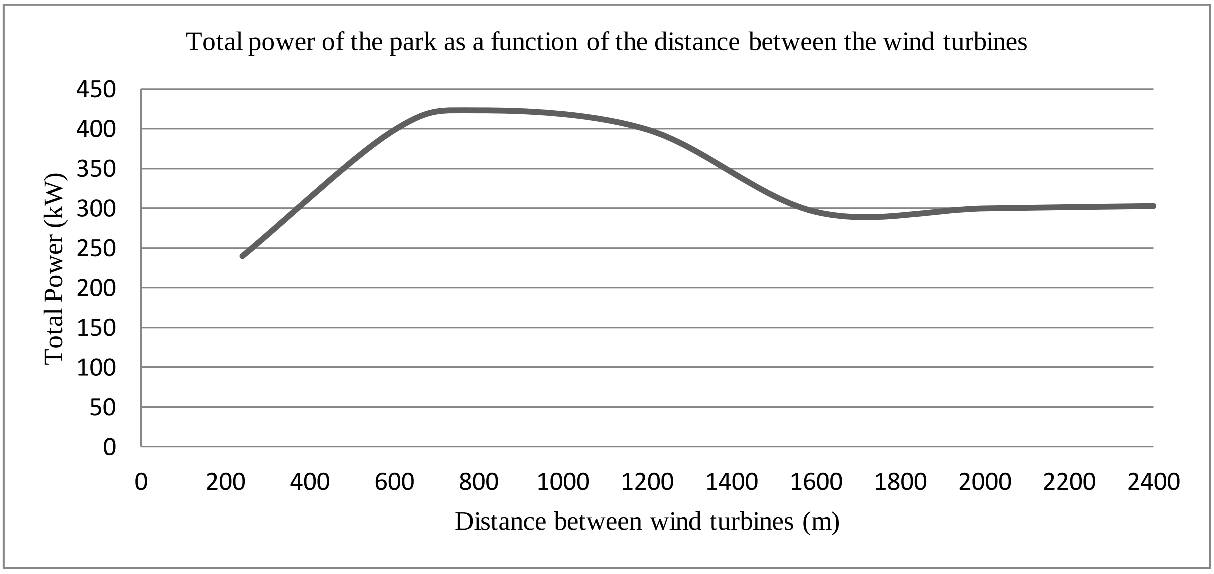

Figure 6 - Variation of park power with distance between wind turbines

Figure 7 shows the Weibull distribution with the wind speed data measured on the turbine nacelle anemometer 1 in hours per year. Thus, we obtained the graph of the annual energy production of turbine 1, Figure 8, which is a result of the multiplication of the frequency by the power, both for the same speed. The annual production of total energy is estimated by means of the area of this graph, thus, turbine 1 presented a total annual production of 1,789 GWh / year. The same procedure was performed for the other turbines and the CEP of each of them was evaluated in each distance between wind turbines analyzed.

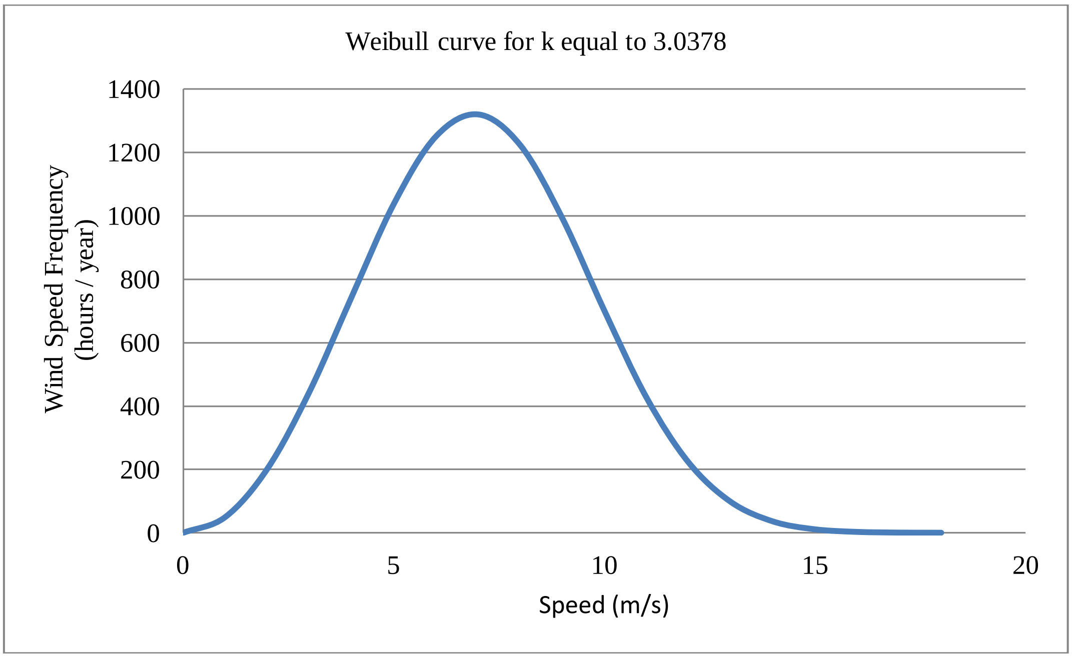

Figure 7 - Weibull distribution of turbine 1 (Frequency in hours / year)

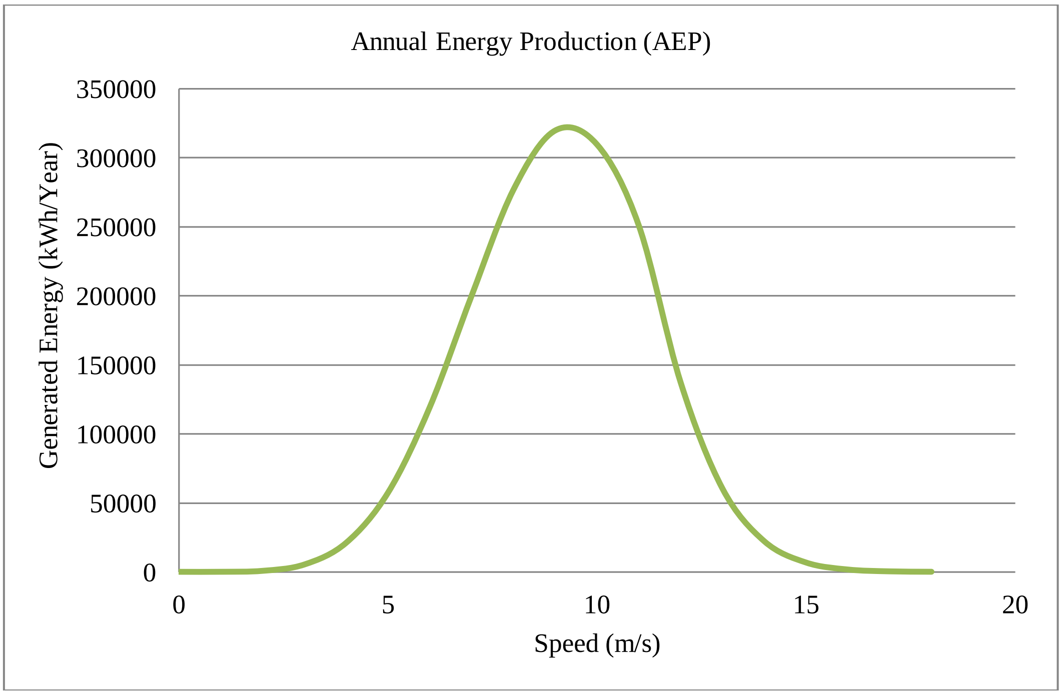

Figure 8 - Annual energy output of turbine 1

Figure 9 shows the *AEP* variation for three distances between studied wind turbines. Although the *AEP* grows as the distance between wind turbines increases, the total production of the wind farm decreases due to the reduction of the available region for turbine construction, which in this case would be limited to three wind turbines (in which case the distance is 30D) If the distance is small (*15D*) the production decreases due to the effect of the treadmill to reduce the *AEP* of each aerogenerator. This confirms that the ideal distance for the construction of four or more wind turbines at the Macau plant is *20D*, which is in accordance with the literature recommendation.

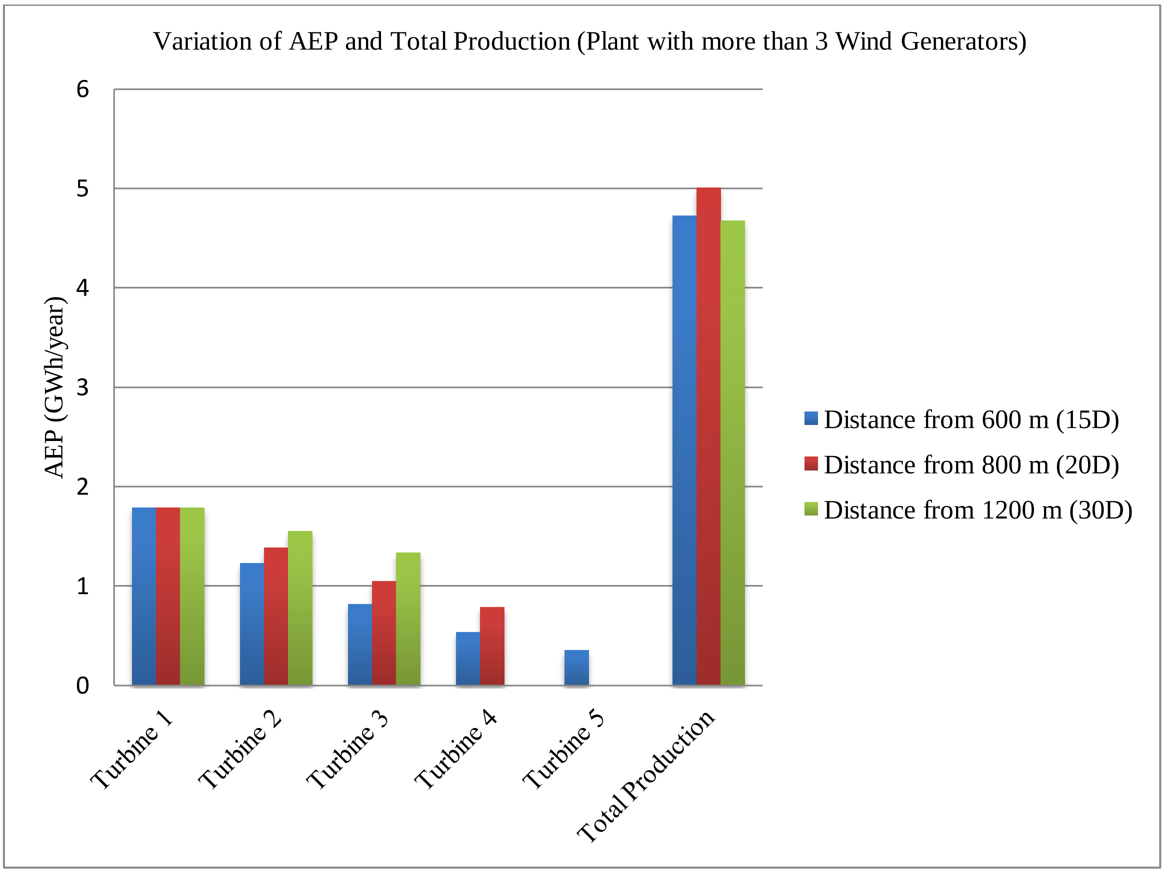

Figure 9 - Variation of AEP and Total Wind Turbine Production

After the study of the layout and generated power of each turbine of the wind farm, the relationship between the speed measured in an anemometric tower and an anemometer in the nacele was evaluated by means of a transfer function, which allowed to construct the graph of the power curve With data provided by the nacelle. Fig. 10 shows the graphs with corrected velocity data (V_{free}), red curve, and with data from the nacelle and the tower, blue curve. It is possible to observe that the function has adapted well to the data, so it is possible to find the power curve with the corrected data.

Figure 11 shows the power curves plotted with tower data (blue curve) and corrected data (red curve). It was observed that the difference between the results was minimal and the corrected data curve did not reach the end of the tower data graph due to the limit of available speed values, where the last speed value found was *10.86* m/s for the corrected data and *18.3* m/s for the tower data, leading to a red curve interruption of *10.86* m/s. Further to this, it has been seen that you can use the transfer function to relate tower and nacelle data effectively.

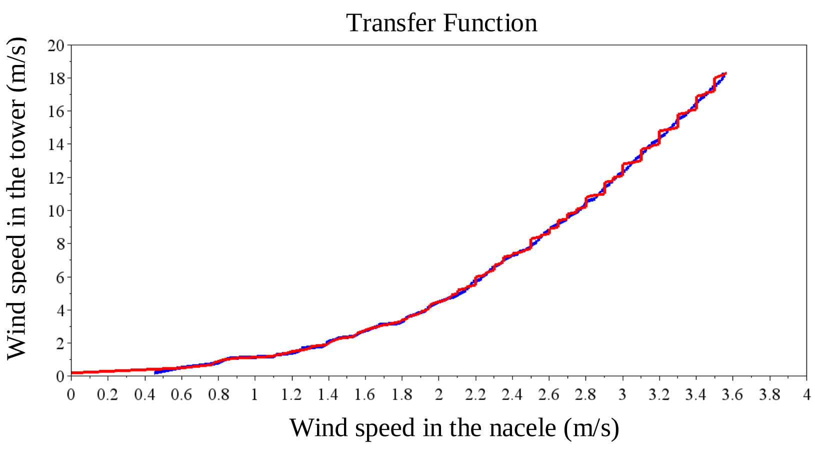

Figure 10 - Graphs with corrected data and nacelle and tower data

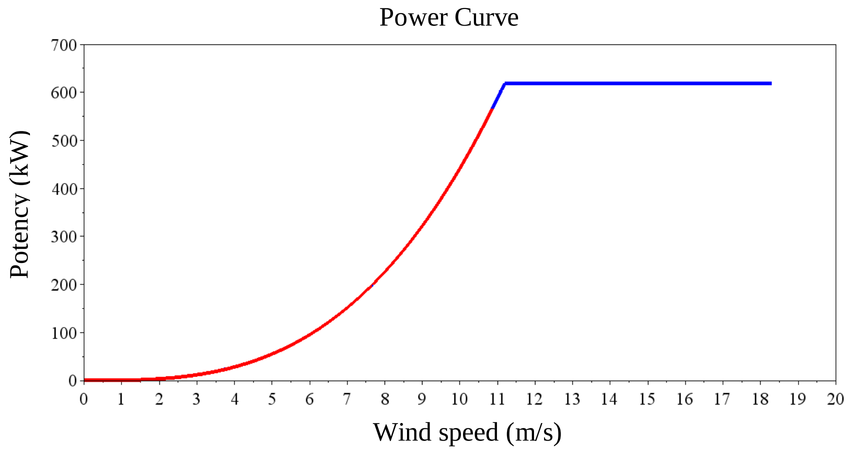

Figure 11 - Power curve with data corrected and with tower data

6. CONCLUSIONS

Considering that it is possible to invest in the construction of more than three wind turbines in a region of *2400* m (*60D*), it can be concluded that: Although the wake effect is reduced as the distance between the wind turbines increases, there is a limit for this distance, for Which if it is very high entails a much greater need for space and losses in the total energy production of the park due to the reduction of the number of turbines; A smaller distance between wind turbines implies in the loss of power generation of the park due to the wake effect increase; It is necessary to find a distance that optimizes production for each case in which it is desired to build a wind farm, considering the amount of wind turbines that will be built and the region available for installation of the wind farm; The distance between aerogenerators required for the park in Macau not to decrease its annual energy output should be *800* m (*20D*).

With respect to the transfer function, it was concluded that: The curve with the corrected data was accurately adapted to the data of the anemometric tower; The graph of the power curve with the corrected data presented the same behavior of the power curve with data of the anemometric tower; The results are not for the Macau Park, due to the lack of wind speed data of a tower in this region, however the algorithm showed that the transfer function can be used to estimate the power of a wind turbine. Speed data were available the result would be satisfactory.

7. BIBLIOGRAPHIC REFERENCES8

Ackermann, T. Wind power in power systems. 2. ed. Sussex do Oeste: John Wiley & Sons, Ltd, 2012.

Albers, A.; Klug, H.; Westermann, D. Power performance verification. In: EWEC-CONFERENCE-. [S.l.: s.n.], 1999. p. 657–660.

Araújo, Maria Regina, O. P., Estudo Comparativo de Sistemas Eólicos Utilizando Modelos Probabilísticos de Velocidade de Vento. Dissertação de mestrado. Rio de Janeiro, RJ - Brasil, 1989.

Burton, T. et al. Wind energy handbook. [S.l.]: John Wiley & Sons, 2000.

Catalão, J. P. Electric power systems: advanced forecasting techniques and optimal generation scheduling. [S.l.]: CRC Press, 2012.

Choi, J.; Shan, M. Advancement of jensen (park) wake model. In: Proceedings of the European Wind Energy Conference and Exhibition. [S.l.: s.n.], 2013. p. 1–8, 2013.

ENERGÉTICA, M. de Minas e Energias e Empresa de P. Plano decenal de expansão de energia 2022. Brasília: MME/EPE, 2013.

González-Longatt, F.; Wall, P.; Terzija, V. Wake effect in wind farm performance: Steady-state and dynamic behavior. Renewable Energy, Elsevier, v. 39, n. 1, p. 329–338, 2012.

Hau, E. Wind Turbines: Fundamentals, Technologies, Application, Economics. 2. ed. Sidcup: Springer, 2005.

Jain, P. Wind energy engineering. Nova Iorque: McGraw Hill Professional, 2011.

Martínez, A. C. Principios de conversión de la energia eólica. In: Amenedo, J. L. R.; Díaz, J. C. B.; Gómez, S. A. (Ed.). Sistemas Eolicos de Produccion de Energia Electrica. Madrid: Rueda, S.L., 2003. cap. 2, p. 27–95.

Mendonça, Ricardo Barros. Modelagem de Usinas Eólicas através de um processo de Markov e Técnicas de Confiabilidade para a Estimativa Anual da Energia Produzida. Natal, RN. Dissertação de mestrado, Universidade Federal do Rio Grande do Norte - UFRN, 2009.

Rohatgi, J. S., Wind Characteristics - An analysis for the generation of wind power. Published by Alternative Energy Institute, Texas, USA, 1994.

Sá, Franciene Izis Pacheco. Efeito da esteira de aerogeradores sobre a produção do parque eólico de Beberibe. Pós Graduação em engenharia mecânica. Dissertação de mestrado, UFSC, Florianópolis, 2015.

Stankovic, S.; Campbell, N.; Harries, A. Urban wind energy. Londres: Earthscan, 2009.

Vermeer, L.; Sørensen, J. N.; Crespo, A. Wind turbine wake aerodynamics. Progress in aerospace sciences, Elsevier, v. 39, n. 6, p. 467–510, 2003.

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