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STUDY OF MULTIPLE WAKE EFFECT ON THE ENERGY PRODUCTION OF WIND FARMS

Andressa Azevedo Jamar
Gabriel Ivan Medina Tapia
Universidade Federal do Rio Grande do Norte, Department of Mechanical Engineering, Natal, Brazil
andressajamar@hotmail.com
gmedinat@ct.ufrn.br

***Abstract**. This paper presents the development of an algorithm to study the influence of the wake effect on the energy production of a wind farm considering the multiple wake model. The proposed algorithm calculates the input speed according to the shadowed area of the wake for each wind turbine to determine the energy production, the energy efficiency and the capacity factor of a wind farm. From the results obtained in the simulation, it can be notice the influence of the wake effect in the productivity parameters because a large number of wind turbines decreases the energy efficiency of the park since more aerogenerators become susceptible to the wake effect. The distance between wind turbines influences the production capacity of a plant, therefore, it is essential to evaluate the layout of a wind farm, prior to its installation.*

***Keywords:** wake effect, energy production, wind farm, wind power*

1. INTRODUCTION

The increase in world energy demand due to a growth of the world consumption capacity cause concern in how to supply this demand, once the provision of energy is related with the price of fossil fuels that besides being harmful to the environment are limited due possible exhaustion of the oil reserves in the next decades. Because of that, investments in alternatives energies becomes a better choice to complement the energy structure of a country. According to the Global Wind Energy Council (GWEC), in 2016, Brazil ranked the 5th position in the world ranking expansion of installed wind power generation capacity, having an increase of 2,014 Megawatts of energy. Due to the relevance of this energy source, it is necessary to study factors that can influence the generation of energy for a wind power project in order to obtain the highest energy yield in a delimited space (Couto; Farias, 2013)

Wind turbines extract energy from the wind to produce electricity; therefore, the wind leaving the turbine must have a lower speed and a turbulent flow, decreasing the amount of available energy, as a consequence, the energy production of a wind turbine a downstream decrease (Martínez, 2013). This phenomenon called wake effect, one of the most important factors for the loss of productivity. As the wind moves away from the wind turbine, the wake begins to dissipate and the wind starts to return to the initial flow condition (González *et al.*, 2010).

Therefore, before the installation of a wind farm, it is essential to evaluate the best use of the available area considering the wake effect, because neglecting it may lead to an overestimation of the park's productivity (Couto; Farias, 2013).

This paper intends to evaluate the problem of the loss of productivity in a wind farm due to the effect of multiple wakes, starting from the analysis of how the positioning of the wind turbines can affect this parameter.

2. METHODOLOGY

2.1 Jensen wake model

The wake model studied in this paper was proposed by Jensen (1984), and it is used in softwares such as WAsP, WindFarmer and WindPRO (Renkema, 2007), which is based on the linear expansion principle of the wake, as seen in Fig. 1, simplifying the calculations.

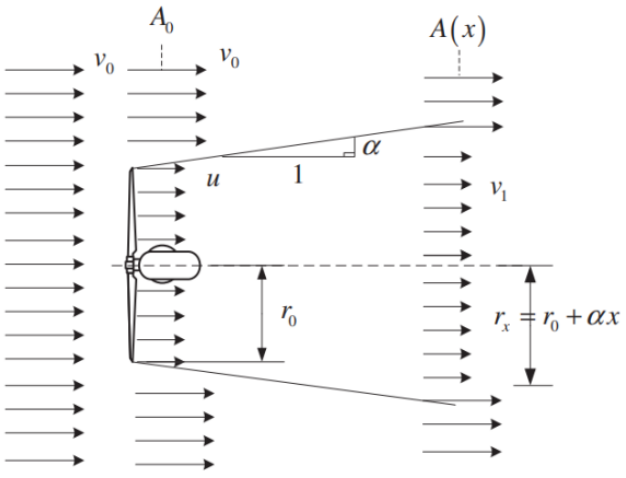


Figure 1. Jensen's wake model (González-Longatt, 2012).

2.1.1. Jensen model for a single wake

The wind flow after passing through the wind turbine propellers will tend to recover its initial condition, resulting in an increase in the diameter of the wake, considered by Jensen (1984), linear and proportional to the distance, as seen in Fig. 1. The Eq. (1) calculates the radius of the wake effect.

$$r_x = r_o + \alpha x \tag{1}$$

Since r_x is the radius of the wake, r is the radius of the rotor, α is the decay coefficient of the wake and x is the distance. The value of α can be determined by Eq. (2) and depends on the height of the turbine hub, h, and z_o the average roughness of the soil.

$$\alpha = \frac{0{,}5}{ln\left(\frac{h}{z_o}\right)} \tag{2}$$

2.1.2. Mutiple wake model

When the wake intercepts the area of a downstream wind turbine, it is shaded by the turbine that caused the wake, causing a decrease in the productivity of the park (Zhang; Wang, 2009). This results in a multiple wake effect illustrated in Fig. 2.

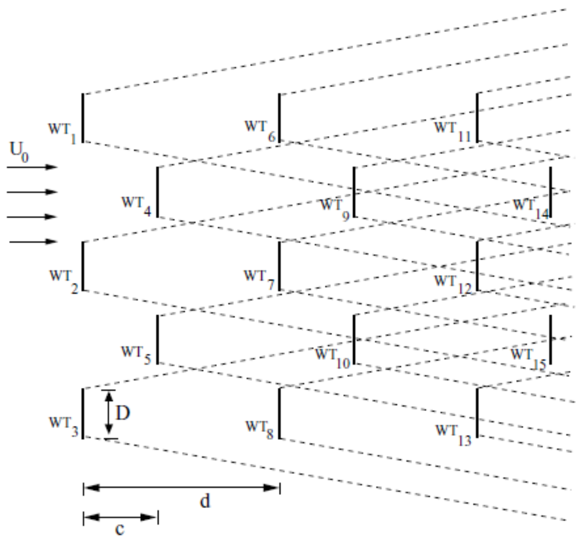


Figure 2. Influence of multiple upwind turbines on effective wind speed (Sethi *et al.*, 2011).

A wind turbine may be affected, partial or totally, by more than one wake. The influence of each wake on the wind turbine should be analyzed based on the calculation of the shaded area, measured from the degree of overlap between the area of the circular section of the wake and the area of the turbine that undergoes its action, as in Fig. 3 (González et al., 2010).

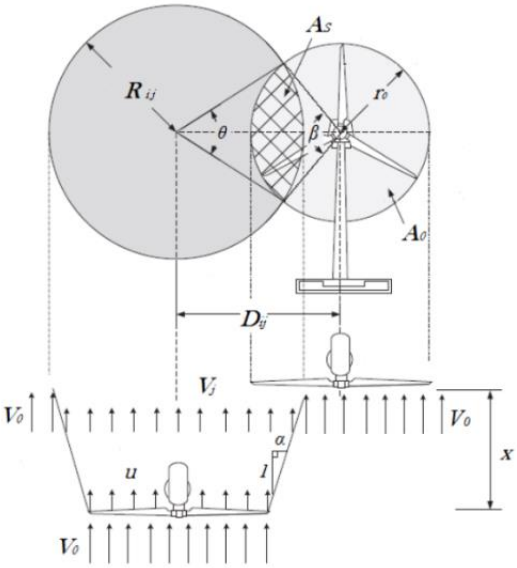


Figure 3. Overlapped area between a wind turbine rotor and a wake stream (González-Longatt, 2012).

In the case of a non-shaded turbine, the input velocity will be the same as that of the available wind in the environment, while in the completely shaded the input velocity will be equal to the wake velocity that shadows it (Couto; Farias, 2013). To calculate the area shaded by the wake, can use trigonometric relations that result in Eqs. (3), (4) and (5).

$$A_s = r^2\big(\theta - (sen\theta cos\theta)\big) + {R_{ij}}^2(\beta - (sen\beta cos\beta)) \quad (3)$$

$$\theta = cos^{-1}\left(\frac{r^2 + D_{ij}^2 - R_{ij}^2}{2D_{ij}r}\right) \quad (4)$$

$$\beta = cos^{-1}\left(\frac{R_{ij}^2 + D_{ij}^2 - r^2}{2D_{ij}R_{ij}}\right) \quad (5)$$

Where A_s is the area shadowed by the upwind turbine, θ is the angle between the center of the circle corresponding to the wake and the points of intersection between said circumference and the circumference corresponding to the area swept by the wind turbine. Besides that, β is the angle between the centers of the circle corresponding to the swept area and the point of intersection between this circumference and the circumference of the wake. R_{ij} the radius of the wake incident on the downstream wind turbine, D_{ij} the distance from the center of the wake to the center of the shaded wind turbine and r the radius of the turbine rotor (Couto; Farias,2013).

When it occurs overlapping of wakes, the input velocity in a wind turbine is modeled differently, considering a weighting in the model proposed by Jensen (Sethi *et al.*, 2011).The model of Sethi (2011) gives the equation of the velocity incident on a wind turbine given by Eq. (6)

$$V_j = V_o\left(1 - (1 - \sqrt{1 - C_T})\frac{D^2}{A_O}\left(\frac{x_{ij}}{2R_{ij}^2}\right)\right) \quad (6)$$

Where V_j is the resulting input velocity in the turbine j, V_0 is the free-flow velocity, D is the rotor diameter, A_0 is the rotor swept area, R_{ij} is the wake radius performed by the i wind turbine on a j wind turbine. Furthermore, x_{ij} is a factor that depends on the shadowing condition of turbine *j*, which equal to 1 when fully shadowed and equal to the shadowed areas sum when partially shadowed.

2.2. Calculation of energy production

The power curve relates the output power of the wind turbine to the incident speed (Hau, 2013) and is found from Eq. (7), where P_M is the maximum power extracted from the wind turbine, P the available wind power, c_p the power coefficient, A_r the rotor area, ρ the specific mass and V_o the wind speed.

$$P_M = c_p P = \frac{1}{2} c_p \rho A_r V_o^3 \tag{7}$$

To understand the productivity of a wind farm, the capacity factor (*CF*), given in Eq. (8), is defined as the ratio of the energy produced by a wind turbine over the energy that could be generated if this wind turbine operated in the maximum power condition (Hau, 2013).

$$CF = \frac{Real\ Production}{Maximum\ Power} \tag{8}$$

2.3. Algorithm for calculating energy production

In order to evaluate the influence of the multiple wakes in a wind field, an algorithm has been developed in Matlab Software that receives data from the layout of wind turbines, the dimension of the wind farm, the value of the average wind speed, data concerning the location of the park and wind turbine data. Through this information and adopting the model proposed by Jensen (1984), for calculations of the influence of the wake radius, the software calculates the influence of shading in each wind turbine from the Eq. (3). With this information it is possible to calculate the speed incident in each aerogenerator considering the area of shading and, consequently, it is possible to estimate the energy output of each turbine, the efficiency of the layout and capacity factor of the wind farm. The procedure for obtaining this information is illustrated in Fig. 4.

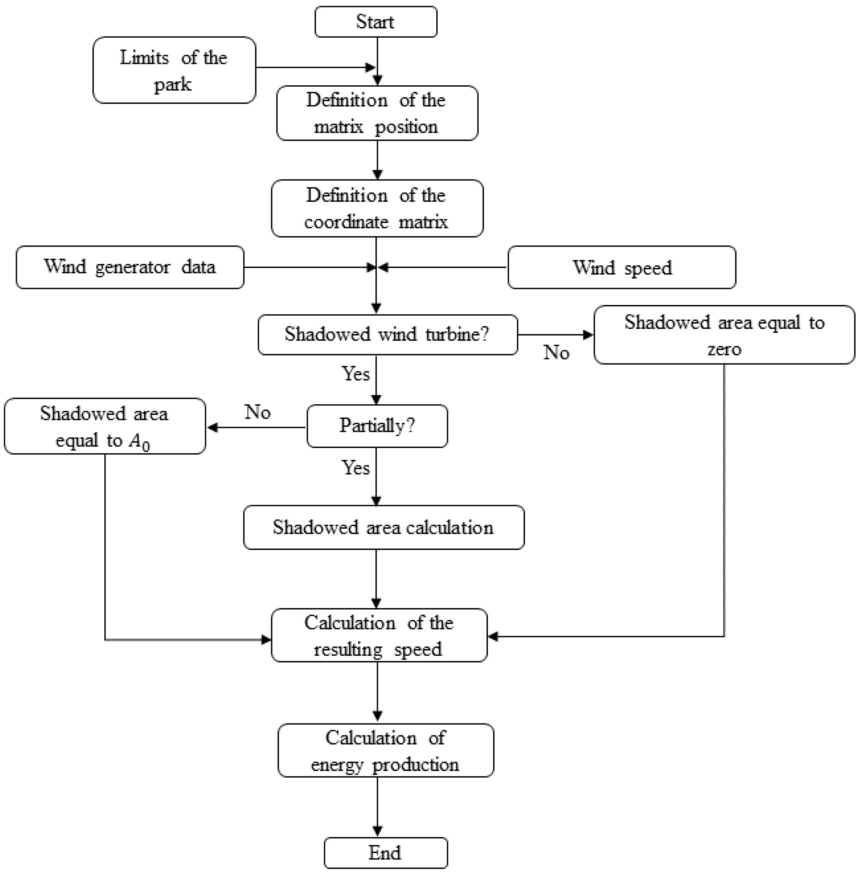


Figure 4. Flow chart of the algorithm (Couto; Farias,2013)

The turbines considered in this work for calculation purposes are from Vestas model V90 – 3,0 MW which has 90 m in diameter and 80 m in height, in addition, its power curve was provided by the manufacturer as seen in Fig. 5. The value of 0.3 was adopted for the roughness of the terrain (Mosetti *et al*, 1994), the average wind speed was estimated through the Atlas of Brazilian Wind Potential (Amarante *et al*, 2001), which is around 9.0 m/s to the north coast of Rio Grande do Norte. Furthermore, the wind field used in the simulation has an 1800x1000 m dimension.

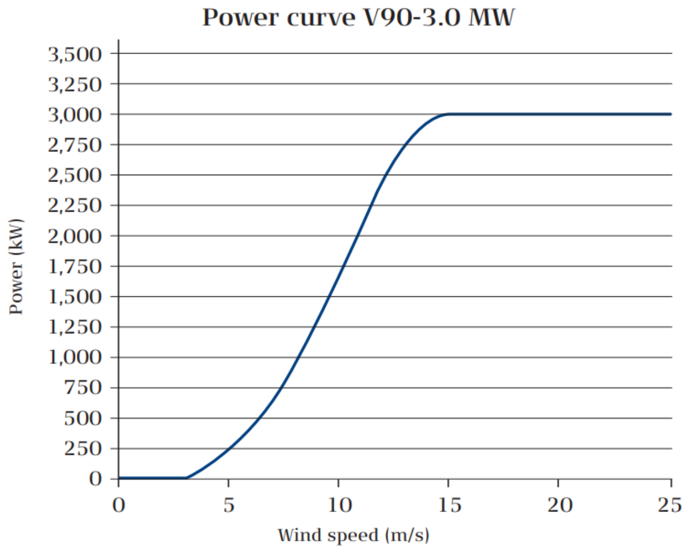


Figure 5. Power curve for V90-3.0MW (Vestas Wind Systems).

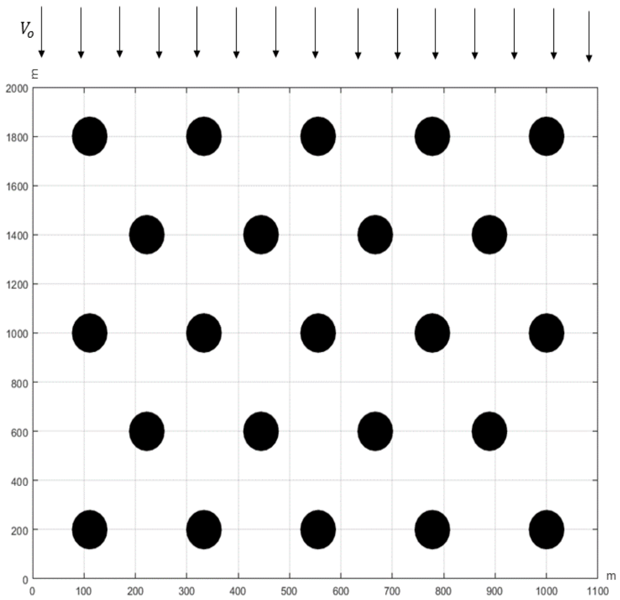
3. RESULTS AND DISCUSSIONS

In the direction to validate the data obtained by the simulation, the results were compared with Couto and Farias (2013) as seen in Tab. 1. The results obtained by Couto and Farias (2013) are for a wind farm of 2000x2000 m which contains 30 turbines and has undergone an optimization process. By evaluating the results it is possible to perceive a small difference, which occurs because the size of each wind farm evaluated is not the same as well as the layout of turbines, but it is still possible to see a relation between the results so that the values obtained in the simulation of the algorithm are within the expected when compared with similar simulations.

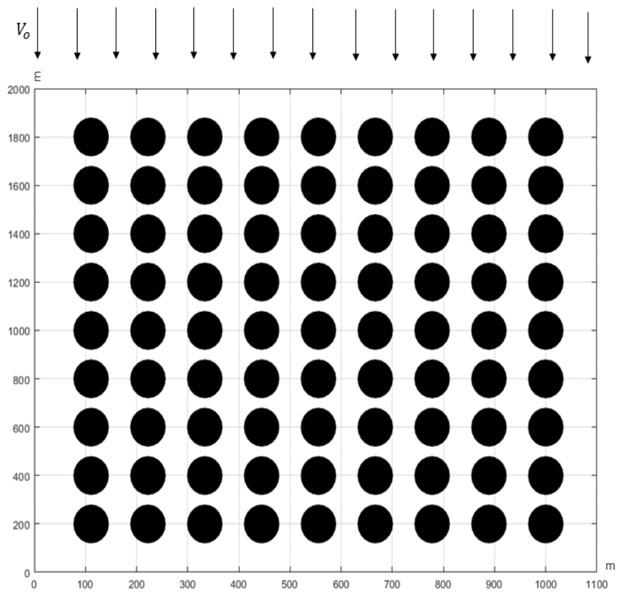
Table 1. Comparison of results with the literature

	Number of turbines	Total Production (kW)	Efficiency (%)	CF (%)
Algorithm	30	52891	90,18%	57,33%
Couto and Farias	30	54932	87,1%	61,0%

The algorithm simulates two layouts with extreme and different configurations for wind turbines, as can be seen in the Fig. 6, as a way to evaluate the behavior of the wake effect in extreme cases. First, by evaluating a more spaced configuration and later on a configuration with closer turbines. Where the x and y axes indicate the positions of the aerogenerators. In Fig. 6a, which represents the first layout configuration, the wind turbines are distributed in a spaced and symmetrical manner, represented by black dots. In Fig. 6b, which represents the second configuration, each wind turbine is also represented by black dots and are as close as possible from the park coordinates so that the largest amount of wind turbines can be obtained.



(a)



(b)

Figure 6. Layout of the wind farm: (a) first configuration, (b) second configuration

From each configuration, tests were performed to evaluate the influence of the wake effect in the energy production, the efficiency of the layout and capacity factor of the wind farms. The Tab. 2 shows the results of this verification.

Table 2. Simulation results for comparison of the two layouts

	Number of turbines	Total Production (kW)	Efficiency (%)	CF (%)
Configuration 1	23	41203	91,63	58,26
Configuration 2	81	77834	49,15	31,25

It is possible to notice that the configuration 2 has the highest total energy production due to the number of turbines, however, the efficiency, as well as the capacity factor are smaller when compared to configuration 1 which has a smaller number of turbines. Herewith, it is possible to prove the influence of multiple wakes in a wind farm, because the increase in the number of turbines impaired the energy efficiency of the park.

Another way of evaluate the loss of productivity due to the effect of multiple wakes is through the variation of the rotor diameter of the wind turbine, for that, a new simulation was performed comparing different diameters and analyzing the energy efficiency behavior. For this simulation, a new layout was analyzed, exposed in Fig. 7, which has 41 turbines and the result is shown in the Tab. 3.

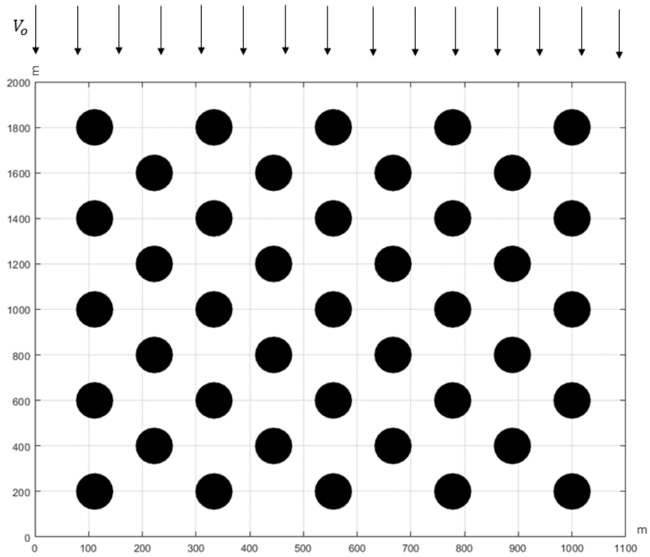


Figure 7. Layout of the wind farm for the simulation of comparison of the diameters

Table 3. Simulation results for comparison of the diameter

Diameter (m)	Total Production (kW)	Efficiency (%)	CF (%)
90	41742	52,08	33,11
80	50026	62,41	39,6
70	60318	75,25	47,84

Evaluating the results obtained in this simulation it is possible to note that as the rotor diameter decreases, the total production, the efficiency and the capacity factor increase. This indicates that the wake effect also depends on the diameter of the rotor because the larger the diameter the greater the radius of reach and shading for turbines that are downstream, thus reducing, the productivity of the park.

4. CONCLUSION

In order to deploy a wind farm in a limited region without high productivity losses, it is necessary to evaluate the positioning of the wind turbines as a way to reduce the influence of the wake effect, because a decrease in the incident wind speed is less pronounced when the wind turbines are farther apart. To study the influence of this phenomenon, a computational algorithm was developed that evaluates the production of a wind farm considering the influence of the effect of multiple wakes and capable of estimating the total production, efficiency and capacity factor of a farm. Through this algorithm it was verified the necessity of a previous study of a layout before the installation of wind towers in order to have the least loss of energy efficiency due to the multiple wake effect. Finally, the results obtained with previously developed studies were compared which allowed the conclusion that the values obtained by the simulation are consistent with the literature, validating their results.

5. ACKNOWLEDGMENTS

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