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STUDY OF WAKE EFFECT IN WIND FARMS APPLIED TO THE STATE OF RIO GRANDE DO NORTE

Matheus de Oliveira Camelo
Gabriel Ivan Medina Tapia
Universidade Federal do Rio Grande do Norte, Departamento de Engenharia Mecânica, Laboratório de Sistemas Térmicos e Energias Alternativas (LSTEA). Campus Universitário Lagoa Nova, CEP 59078-970, Natal, RN, Brasil.
matheusocamelo@gmail.com
gmedinat@ct.ufrn.br

Abstract. *This paper studies the influence the wake effect of wind turbines has on the energy production and the efficiency of wind farms with wind and terrain characteristics specific to state of Rio Grande do Norte. To represent the wake effect in wind farms, it was used a multiple wake model applied to Jensen wake model. The model was implemented as a MATLAB computational algorithm which receives as input data a wind farm layout and characteristics of the chosen wind turbine and the terrain and it calculates the total output power of the park. The algorithm also returns layout efficiency, given by the ratio of total output power with to without wake effect, and capacity factor, given by the ratio of the real total output power to the rated power of the farm. The first results confirmed the algorithm's ability to perform the requested analysis. Moreover, the adopted mathematical model provided a satisfactory description for multiple wakes phenomenon. Other results were obtained with local characteristics of Rio Grande do Norte being applied to several wind farm layouts to assess the consequences of wake effect. It was proved that the impact of wake effect is very significant on the power generation of a wind farm. Therefore, the layout of wind turbines must be designed in order to minimize this impact.*

Keywords: *wake effect, Jensen model, wind energy, wind farm*

1. INTRODUCTION

Wind energy is currently one of the energy sources with increasing importance in world power generation, in opposition to traditional energy sources, focused on fossil fuels. In this context of great expansion, Brazil and, specifically, the state of Rio Grande do Norte (RN), have taken part in the process. Good utilization of Brazilian wind potential would improve the national electrical system performance, since it has been identified a geographical complementarity between hydroelectric power and wind power in the country: the regions with the greatest wind power potential are at the ends of the electrical system lines, far away from the main hydroelectric power plants (Amarante et al., 2001). One of those regions is the Northeast Region of the country, where the state of Rio Grande do Norte is located.

The main role of Northeast Region and Rio Grande do Norte in Brazilian wind potential was identified since the first studies about this subject, in the 1970s. Coastal regions were soon identified as the most promising ones and a test field was installed at Barreira do Inferno Launch Center, on the coast of Rio Grande do Norte. In 1987, a report from Hydroelectric Company of São Francisco (CHESF) pointed out that the highest annual average wind speed at height of 10 m in Northeast Region was 5.5 m/s in Macau, RN. Another report from CHESF suggested in 1996 that it was possible to generate 2,960 GWh/year of electricity by occupying 10% of the coast of Rio Grande do Norte with 500 kW and 600 kW wind turbines. According to the Brazilian Wind Energy Potential Atlas, the coast of Rio Grande do Norte is included in the area with the highest annual average wind speeds of the entire Brazilian coast, both in its northern and eastern parts (Amarante et al., 2001).

The wind energy potential of Rio Grande do Norte was studied in detail in 2003, when three regions of the state were identified as the most promising for wind parks installation: the Northeast of the State and the North/Northwest Coastline, both coastal regions; and the Central Highlands, with elevations of about 700 m in altitude (Amarante et al., 2003).

One of the most relevant phenomena in the studies that precede the installation of a wind farm in a given site is the aerodynamic wake, which may have significant effects on the energy output of that wind turbines cluster. That happens because the mechanical energy that causes the turbine blades movement is extracted from the wind flowing through the blades and decreases the amount of kinetic energy contained in the wind stream. Considering an unchanged air mass flow, the air speed after the turbine must be lower than before it. This low speed field becomes larger as it moves away from the turbine that generated it, and if there are many turbines very close together, inside the same wind farm, the downwind turbines are affected by the wakes of the upwind turbines. As consequence, they receive reduced wind speed, decreasing

their energy output (Hau, 2013). However, as the wind speed in the wake gradually returns to the initial condition, a larger spacing between wind turbines ensures the downwind turbines will receive less reduced wind speeds (Jamar and Tapia, 2018). Figure 1 illustrates the wake phenomenon in a wind park.
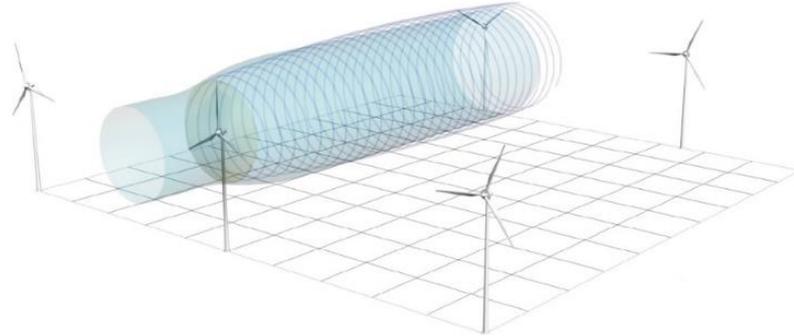

Figure 1. Wake effect of a wind turbine in a wind farm (adapted from Amarante et al., 2001).

The study about the influence of the wake effect on the energy output from wind farms requires the creation of physical-mathematical models capable to calculate the wake behind a wind turbine rotor. The first useable model was Lissaman's one, published in 1977 (Hau, 2013). However, the exact modeling of the wind speeds in a wind farm is quite complicated, requiring data and parameters not always available (González-Longatt et al., 2012). Among the models that attempt to describe the wake effect are Lissaman, Ainslie, Park, Werle and Jensen models and their respective multiple wake models (Silva, 2014).

The aim of this work is to study a simplified mathematical model to represent the wake caused by a wind turbine and the interactions between the wakes of wind turbines in the same wind park. This model must be implemented in a computational algorithm capable to determine the influence of the wake effect on energy output of wind farms. Then the algorithm must receive specific information about the local situation of Rio Grande do Norte, such as wind and terrain data, and be applied to some different arrays of wind turbines in a limited physical space so that it can be evaluated the capability of the chosen model to determine the influence of the wake effect on the energy output of wind farms in Rio Grande do Norte.

2. LITERATURE REVIEW

2.1 Output power of a wind turbine

Before understanding how a wake effect model is able to estimate wind speeds in a turbine wake, it is necessary to understand how the mechanical power extracted by a turbine rotor is related to its incoming wind speed. According to Hau (2013), the available mechanical energy in the air flow is given by Eq. (1), in which P_0 is the total available wind power, ρ is the density of air, A_0 is the wind turbine rotor area and V_0 is the incoming wind speed on the rotor blades.

$$P_0 = \frac{1}{2}\rho A_0 V_0^{3} \tag{1}$$

To determine how much of the energy contained in the wind is converted into mechanical power by the rotor, it was established the power coefficient c_p, defined as the ratio of the power that is extracted by the wind turbine (P) to the total available wind power (P_0). The value of c_p is a specific characteristic from the chosen wind turbine model. In terms of c_p, Eq. (2) determines the mechanical power that is extracted by the turbine as function of the incoming wind speed (Hau, 2013).

$$P = \frac{1}{2}c_p\rho A_0 V_0^{3} \tag{2}$$

The amount of energy that any wind turbine can extract from the wind and convert it to mechanical power is not unlimited. There is an upper theoretical limit for every wind turbine, known as the Betz limit, named after Alfred Betz, a German scientist who was among the first ones to calculate it. Betz limit is the theoretical maximum power coefficient that any wind turbine could reach and its value is $c_p = \frac{16}{27}$. Another characteristic coefficient of a wind turbine is the thrust coefficient c_T and this one is related to the thrust force exerted by the air on the turbine disk. At Betz limit, in which $c_p =$

$\frac{16}{27}$, the thrust coefficient is $c_T = \frac{8}{9}$. That means the theoretical upper limit for the power coefficient is about 0.593 and its corresponding thrust coefficient is about 0.889 (Hau, 2013; Hunsaker and Phillips, 2013). Nevertheless, for practical purposes, the value of c_p reaches 0.45 (Amarante et al., 2003).

Equation (2) can be used to generate the power curve of a wind turbine, also a specific characteristic from the wind generator. The power curve links the incoming wind speed of the wind turbine to the mechanical power converted by it. Figure 2 presents an example of power curve. It can be noted that the rising curve, mathematically defined by Eq. (2), is followed by a constant level of generated power which has no change with the wind speed. This level is the rated power of the wind turbine, the maximum amount of energy it can generate. At very low speeds ($V_0 < 3$ m/s), there is no energy production due to the low wind potential. At very high speeds ($V_0 > 25$ m/s), the wind turbine is turned off to prevent structural damage.
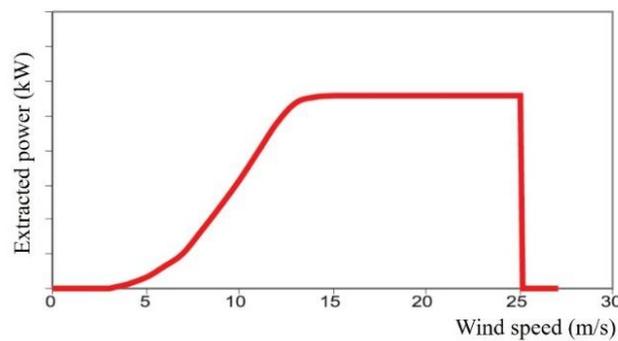

Figure 2. Typical power curve of wind turbines (adapted from Amarante et al., 2001).

2.2 Jensen model for wake effect

The physical-mathematical model that was selected for the studies in this paper was the model developed by Jensen (1983). This is one of the most common models in works concerning the problem of positioning wind turbines in wind farms due to its simplicity in describing the wake effect and to the good obtained results (Silva, 2014). Jensen considered that the diameter of the wake increases linearly with the distance from the turbine. This linear expansion of the wake can be seen in Fig. 3. Thus, the radius of the wake (r) is related to the horizontal distance from the turbine (x) in Eq. (3), in which r_0 is the rotor radius of the wind turbine.
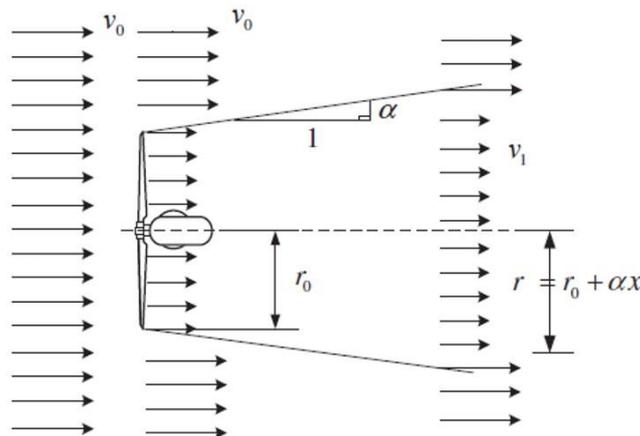

Figure 3. Jensen wake model with linear expansion of the wake (adapted from González-Longatt et al., 2012).

$$r = r_0 + \alpha x \tag{3}$$

The dimensionless term α, which is presented in Eq. (3), is called the entrainment constant or decay coefficient and it determines how quickly the diameter of the wake expands with distance. It is defined in Eq. (4) as function of h, the hub (rotor) height of the turbine, and of z_0, which represents the surface roughness, a value that depends on the local terrain characteristics (González-Longatt et al., 2012).

$$\alpha = \cfrac{1}{2\,ln\left(\cfrac{h}{z_0}\right)} \qquad (4)$$

The equation that determines the wind speed in the wake of the wind turbine as function of the distance downwind the turbine was obtained by Jensen (1983) from a balance of air momentum before and after passing through the rotor. This relation is presented in Eq. (5) as it was expressed by González-Longatt et al. (2012).

$$v_1 = v_0 + v_0\left(\sqrt{1 - c_T} - 1\right)\left(\frac{r_0}{r}\right)^2 \qquad (5)$$

In Eq. (5), v_1 is the wind speed in the wake of the turbine at distance x from the rotor, as it is shown in Fig. 3, v_0 is the free wind speed before passing through the rotor, c_T is the thrust coefficient, mentioned in section 2.1, r_0 is the radius of the turbine rotor and r is the radius of the wake of the turbine, defined in Eq. (3) as function of the distance x (Farias and Couto, 2013).

2.3 Jensen model for multiple wakes

The model developed by Jensen is useful to represent the wake effect of a wind turbine and to calculate the wind speed anywhere in its wake. If there is another wind turbine affected by that wake, its incoming speed is the wind speed at that point in the wake. However, in real wind farms, a downwind turbine is frequently affected by the wakes of several upwind turbines. This causes an overlapping wakes effect, which requires improvements of the standard Jensen model. Figure 4 presents a small random wind park in which it can be seen the phenomenon of overlapping wakes.
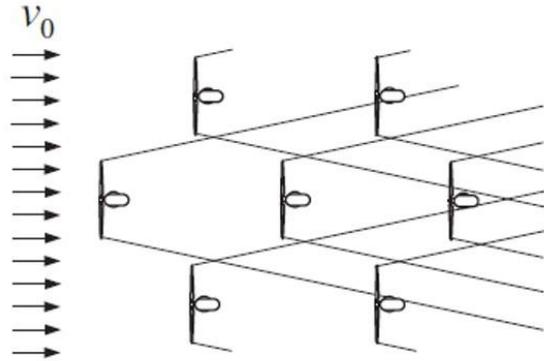

Figure 4. Wind farm with multiple wakes overlapping (adapted from González-Longatt et al., 2012).

To calculate the wind speed in a turbine that is under the effect of multiple wakes, it is necessary to combine the effects of every single wake into a single effect (González-Longatt et al., 2012). That means to merge several wind speeds into an effective input wind speed in each wind turbine (Sethi et al., 2011). To achieve this goal, it is necessary to analyze the shadowing caused in each downwind turbine by all upwind turbines. The shadowing from the wake of turbine i on the rotor of another turbine j is depicted in Fig. 5.

In Fig. 5, it can be seen that the shadowed area A_S can be calculated as function of the lateral distance between the turbines (d_{ij}), the radius of the wake of turbine i (R_{ij}, represented in Fig. 5 as $r_i(x_{ij})$), the rotor radius of the turbines (r_0) and the angles θ and β. By using trigonometry, it is possible to obtain Eq. (6), Eq. (7) and Eq. (8) (Farias and Couto, 2013).
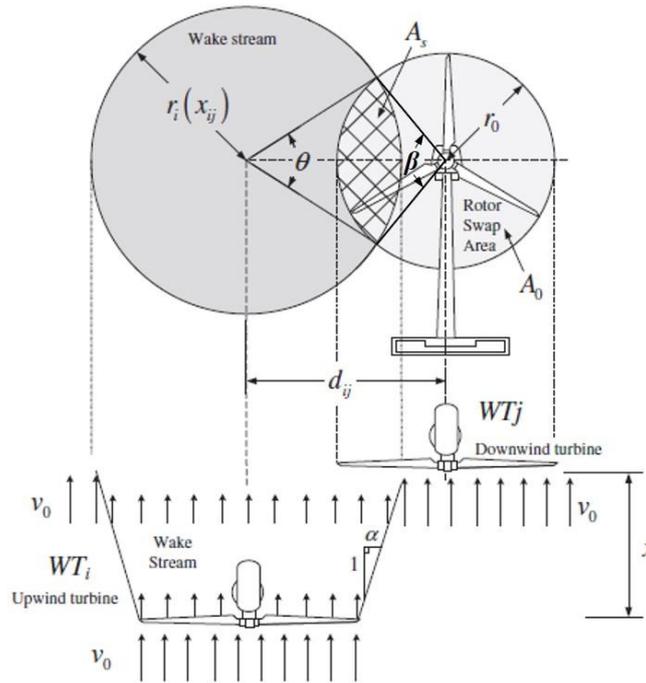
Figure 5. Wake of an upstream turbine shadowing the rotor swept area of a downstream turbine (adapted from González-Longatt et al., 2012).

$$A_S = r_0^2(\theta - (sin\theta cos\theta)) + R_{ij}^2(\beta - (sin\beta cos\beta)) \qquad (6)$$

$$\theta = cos^{-1}\left(\frac{r_0^2 + d_{ij}^2 - R_{ij}^2}{2d_{ij}r_0}\right) \qquad (7)$$

$$\beta = cos^{-1}\left(\frac{R_{ij}^2 + d_{ij}^2 - r_0^2}{2d_{ij}R_{ij}}\right) \qquad (8)$$

From the calculation of the areas in every downwind turbine that are shadowed by the wakes of every upwind turbine, given by Eq. (6), it is possible to determine the resultant incoming wind speeds in the downwind turbines. The equation that links the shadowing of a wind turbine to its resultant incoming speed was adapted from González-Longatt et al. (2012), that considered a weighting in Jensen model, and it is presented in Eq. (9).

$$v_j = v_0 - \sqrt{\sum_{i=1}^{n} x_{ij}(v_{ij} - v_0)^2} \qquad (9)$$

In Eq. (9), v_j is the resultant incoming speed in wind turbine j, v_0 is the undisturbed wind speed, n is the total amount of turbines in the wind farm, i is the turbine that causes shadowing and v_{ij} is the wind speed in the wake of turbine i calculated at the position of turbine j. This speed is given by Eq. (5). The factor x_{ij} represents the shadowing condition of turbine j by turbine i and it is equal to the ratio of the shadowed area on j by i, given by Eq. (6), to the total area swept by the blades (González-Longatt et al., 2012).

2.4 Efficiency and capacity factor

To evaluate the quality of wind turbines layouts inside wind farms, two parameters are used: layout efficiency and capacity factor. The efficiency of the wind farm or wake coefficient (González-Longatt et al., 2012) may be represented as η_{farm} and it is defined as the ratio of the total output power from the park considering wake effect to the total output power from the park if every wind turbine received undisturbed wind. The capacity factor, which may be represented as CF, is defined as the ratio of the total output power from the park considering wake effect to the total output power from the park if every wind turbine operated in rated power, *i.e.* if they kept the highest energy production of the power curve

during the entire operating time (Farias and Couto, 2013). The parameters presented above are used to compare wind farm layouts in terms of quality.

3. METHODOLOGY

In order to evaluate the influence of wake effect in a wind turbines cluster, those equations presented in section 2 need to be applied repeatedly for each wind generator, calculating several values of radius, diameters, shadowed areas, wind speeds and powers. To perform this work, it is essential to apply a computational algorithm that can quickly make all the needed calculations. Therefore, a MATLAB software originally developed by Farias and Couto (2013) was implemented and adapted for the purposes of this paper in a similar way to what was done by Jamar and Tapia (2019).

As input data, the software receives a matrix of positions which represents the wind turbines array in the analyzed wind park. That is a binary matrix in which cells without a turbine receive value 0 and cells with a turbine receive value 1. The software also receives data concerning the terrain where the park will be installed: the surface roughness (z_0), the free wind speed in that location (v_0) and the wind farm dimensions, supposing it as rectangular. With these dimensions and the matrix of positions, the algorithm calculates the distances between cells and generates an ordered pair for each wind turbine in two coordinate axes x and y. The coordinates are useful to determine the distances in x and in y between any two turbines. Furthermore, each existing turbine receives a number to identify it until the end of the algorithm. Figure 6 shows a binary matrix of positions being transformed into a wind farm with numbered turbines on a coordinate system x and y. As it can be noticed in Fig. 6, the algorithm which was developed is limited to analyses with unidirectional wind.
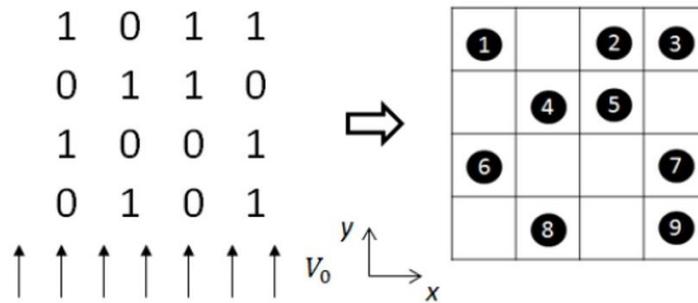

Figure 6. Layout of a wind farm represented as binary matrix and as grid with x and y axes (adapted from Farias and Couto, 2013).

Other input data for the software concern characteristics of the wind turbine model chosen for the simulation: the rotor radius of the turbine (r_0), the hub height of the turbine (h) and the power curve of the wind generator, which is usually provided by the manufacturer. The power curve associates several wind speed values to the corresponding power that is extracted by the rotor. It may also include a series of thrust coefficient (c_T) values, because this coefficient changes with the wind speed in real situations (Farias and Couto, 2013).

The next step in the algorithm is to calculate the radius of the wakes caused by all upstream turbines on all downstream turbines. After calculating the radius of the wakes, the software immediately calculates the shadowed areas of each turbine (A_S) using Eq. (6), Eq. (7) and Eq. (8) and determines the shadowing factor x_{ij} for each of them. Then the software calculates the effective incoming wind speed in each turbine by using Eq. (5) and Eq. (9). The calculation of the extracted power of each turbine in the park is done by interpolation: the incoming speed of each turbine is interpolated into the power curve and a value for the output power of each one of them is obtained.

The last step in the algorithm is to calculate the total energy output of the wind farm (sum of the powers from all wind turbines), the energy output of the park neglecting wake effect (by interpolating the free wind speed into the power curve and multiplying it by the number of turbines in the park) and the energy output of the park if every turbine operated in rated power (by multiplying the rated power by the number of turbines in the park). Then the software ends by printing values for efficiency and capacity factor of the wind farm, as defined in section 2.4.

4. RESULTS AND DISCUSSION

Before applying the algorithm that was developed to geographic characteristics of Rio Grande do Norte, its correct operation was verified by applying it to wind farm layouts provided by literature, for which the values of total output power, layout efficiency and capacity factor are known. The layouts for comparison were taken from Farias and Couto (2013), whose MATLAB algorithm inspired the one developed for this work. All the analyzed wind farms are represented by 10×10 matrices of positions, which have 100 possible spots to place turbines. For every layout, Farias and Couto (2013) used the same input data, except for the matrix of positions. These data were obtained from Mosetti et al. (1994): the wind farm dimensions are 2,000 m by 2,000 m; the surface roughness of the terrain is 0.3 m; the free wind speed is

12.0 m/s; the chosen wind turbine model has a 40 m diameter and a 60 m hub height, with a thrust coefficient 0.88. The power curve of this turbine, which has a rated power about 620 kW, was also provided by Mosetti et al. (1994) and it is presented in Fig. 7a. The first layout analyzed by Farias and Couto (2013) was also obtained from Mosetti et al. (1994) and it appears in Fig. 7b. In all layout's pictures included in this paper, the wind speed direction is indicated by *V*.

(a)   (b)
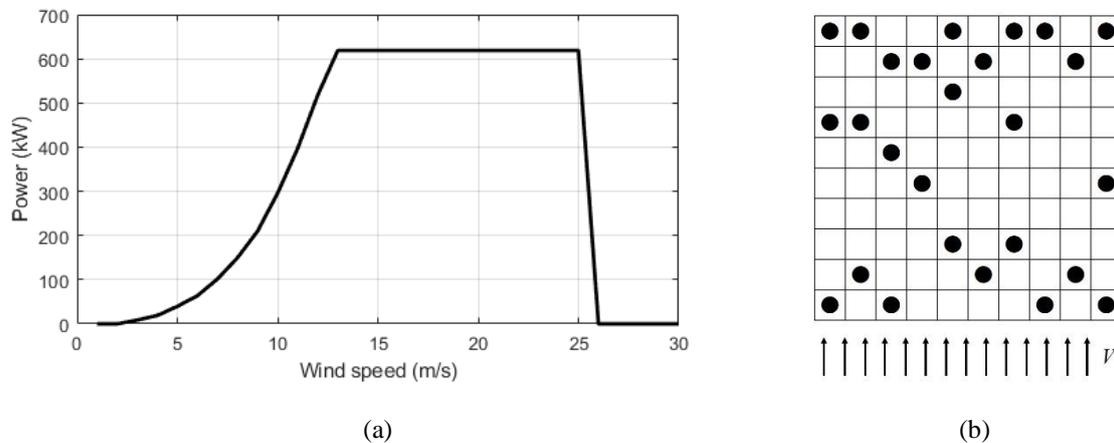
Figure 7. Input data provided by Mosetti et al. (1994): (a) power curve of the wind turbine; (b) wind farm layout (own work based on Mosetti et al., 1994).

According to Mosetti et al. (1994), the layout depicted in Fig. 7b, which has 26 turbines, has a total output power of 12,375 kW and an efficiency of 95%. In its turn, the algorithm developed by Farias and Couto (2013) calculated, for the same layout, an output power of 12,921 kW, an efficiency of 95.5% and still a capacity factor of 80.0%. The software developed in this work got the following values: total power of 12,771 kW, efficiency of 94.9% and capacity factor of 79.4%. It can be clearly noted the similarity between the results obtained in this work and the values found in the literature, what suggests a good operation of the algorithm.

The algorithm was also submitted to other comparison tests, all of them with layouts that were analyzed by Farias and Couto (2013) using the same input data as Mosetti et al. (1994), except for the matrix of positions. Including all layout's pictures in this work would make the paper very long, then Tab. 1 summarizes the output power and efficiency results calculated by the algorithm of this work in comparison to the values obtained by Farias and Couto (2013). The other layouts are an optimized version of the original Mosetti et al. layout and two other layouts, named Layout I and Layout II, in conjunction with their respective optimized versions. As it can be observed, the similarity between results from both works is remarkable.

Table 1. Results obtained in this work compared to results by Farias and Couto (2013).

Layout	Number of turbines	Farias and Couto (2013)		This work	
		Total power (kW)	Layout efficiency (%)	Total power (kW)	Layout efficiency (%)
Mosetti et al. optimized	26	12,985	96.0	12,867	95.6
Layout I	30	14,764	94.6	14,804	95.4
Layout I optimized	30	14,790	94.8	14,562	93.8
Layout II	32	13,467	80.9	12,345	74.5
Layout II optimized	32	15,574	93.6	15,314	92.5

With the application of the developed algorithm to several wind farm layouts and the comparison of the obtained results to literature results, its good operation was confirmed, that is, its ability to receive a wind farm layout and then to calculate its total energy production, layout efficiency and capacity factor. The comparison to the results from Farias and Couto (2013) proved that the values are close enough to confirm the validity of the algorithm and also of the mathematical model that was applied, based on Jensen wake model.

After performing the operation tests of the algorithm, in which the obtained values were compared to already known results, it is possible to apply the algorithm to several situations with different parameters. As part of the objectives of this work, environmental characteristics specific to the state of Rio Grande do Norte were used. They were obtained from the Rio Grande do Norte Wind Energy Potential Atlas (Amarante et al., 2003). An arbitrary location was chosen near the Northeast Coast of the state, where there are high annual average wind speeds and the construction of wind farms is common. According to the maps from the Atlas, at that location the surface roughness of the terrain is about 0.4 m and the annual average wind speed is about 8.0 m/s measured at a 75 m height from the ground. This wind speed was taken

at a 75 m height because the wind turbine model used in this analysis, Vestas V90 – 3.0 MW, has a 90 m diameter and the considered hub height is 80 m. The power curve of this turbine, which is one of the algorithm's input data, is shown in Fig. 8. For the thrust coefficient, the chosen value is 0.88, because it is the same adopted by Mosetti et al. (1994) and because it approaches the theoretical upper power coefficient, 0.593.
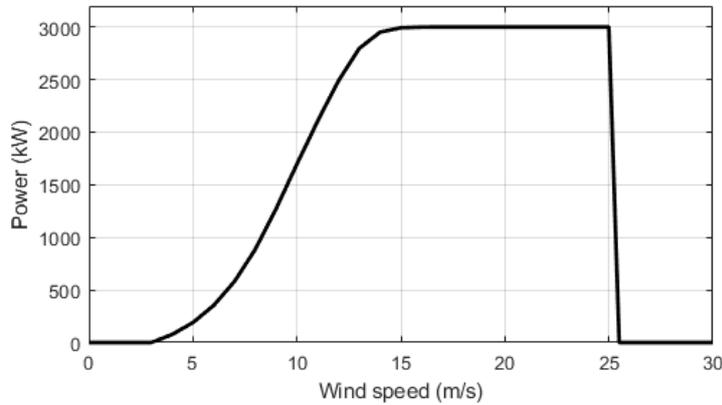

Figure 8. Power curve of the wind turbine Vestas V90 – 3.0 MW (own work based on Farias and Couto, 2013).

The selected input parameters were applied to six wind farm layouts. The layouts submitted to this analysis were created manually with the purpose of evaluating the impact of wake effect on power generation. Therefore, they were designed to simulate situations in which the positioning of the turbines causes a lesser or greater impact of wake effect, thus increasing or decreasing the total energy production. Each park consists of a square land with dimensions 1,500 m by 1,500 m. Each matrix of positions is 10×10 (100 cells), then the shortest distance between two neighboring wind turbines is 150 m. Moreover, 25 turbines were placed in each park.

In layouts 1, 2 and 3, presented in Fig. 9, the objective was improving the park efficiency by reducing the impacts of wake effect. In layout 1 (Fig. 9a), there are five lines with five turbines each and a two cells space between each two turbines (300 m). Although this distance, the turbines are lined up, which intensifies the shadowing of wakes. That is why this layout reached a total output power of only 10,807 kW, efficiency of 48.8% and capacity factor of 14.4%. Layout 2 (Fig. 9b) was adapted directly from layout 1 as an attempt of reducing the impact of the wakes. Several turbines were alternately moved one position to the side, thus occupying the lines which had been unoccupied. Since the number of turbines in the same line was reduced, the wind farm performance significantly increased, reaching a total power of 17,268 kW, efficiency of 78.0% and capacity factor of 23.0%. Therefore, the total output power of the wind farm increased by 6,461 kW without adding new turbines to the farm. Layout 3 (Fig. 9c) was another attempt of improving the park efficiency, by positioning the 25 turbines on diagonals in order to avoid turbines to be lined up in the direction of wind. The result was not so much better than layout 2, with total power of 17,577 kW, efficiency of 79.4% and capacity factor of 23.4%. Nevertheless, it was the most efficient layout manually obtained in this work.
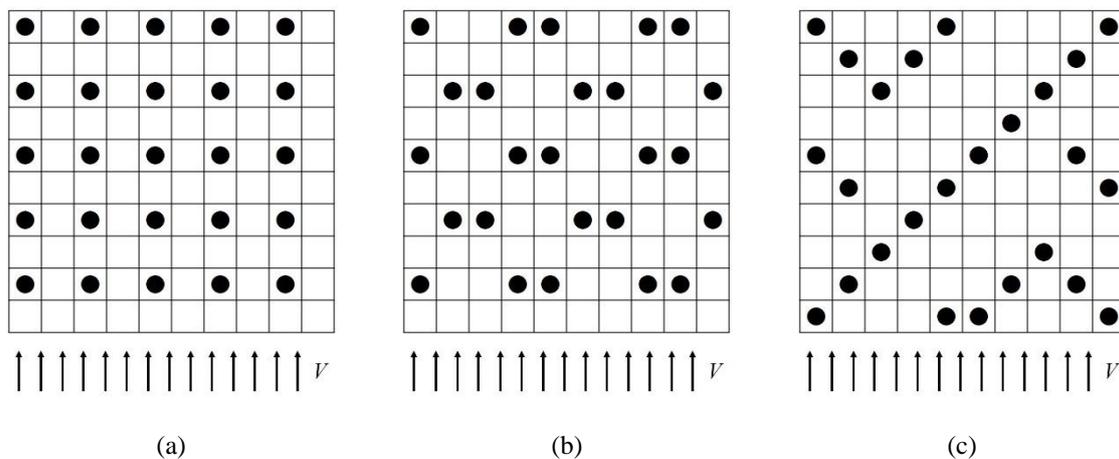

| (a) | (b) | (c) |

Figure 9. Wind farm layouts: (a) layout 1; (b) layout 2; (c) layout 3 (own work).

Layouts 4, 5 and 6, presented in Fig. 10, were created with the purpose of analyzing some extreme cases in which the turbines are as close together as possible, thus increasing the influence of wake effect and decreasing the total power and

the efficiency of the park. In layout 4 (Fig. 10a), 20 turbines were positioned in the first two rows of the wind farm and the remaining five turbines were placed in more central positions, where there are more wakes overlapping. In this situation, the farm has a total power of 11,305 kW, efficiency of 51.0% and capacity factor of 15.1%. The decrease in efficiency was remarkable, although this layout reached higher energy production than layout 1, in which the turbines were lined up. Layout 5 (Fig. 10b) has an array of five lines with five turbines each, as in layout 1, but with a minimum distance of 150 m. The high density of turbines in a small area intensified the impact of wake effect, reducing the total power of the wind farm to 6,813 kW with efficiency of 30.8% and capacity factor of 9.1%. In its turn, in layout 6 (Fig. 10c), 20 turbines were placed in two full lines, in the same direction as the wind speed, and the other five were positioned at the end of the beside lines, where the overlapping of wakes is probably higher. As expected from this extreme situation, the total output power was very low, only 5,921 kW, with efficiency of 23.9% and capacity factor of 7.1%.
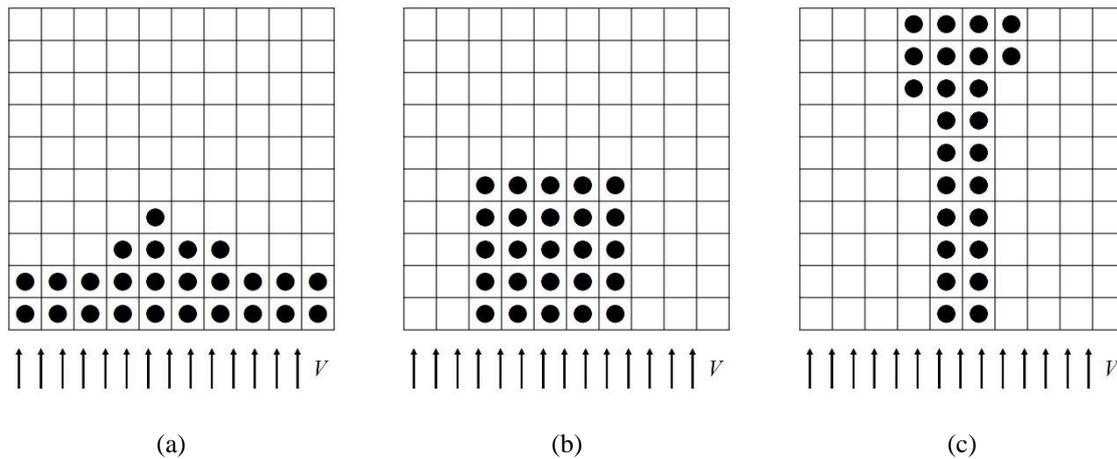

| (a) | (b) | (c) |

Figure 10. Wind farm layouts: (a) layout 4; (b) layout 5; (c) layout 6 (own work).

The latest layouts submitted to be analyzed by the developed algorithm evidenced clearly how significantly the wake effect can affect the energy production of a wind farm and generate losses if the array of wind turbines is not made carefully. However, it is important to note that, for layouts 4, 5 and 6, a better use of the total available area was not attempted. The turbines are concentrated in a small space and the remaining land is unoccupied. Naturally, to increase power generation and efficiency of a wind farm, turbines should be spread as far as possible over the land.

Table 2. Results obtained for arbitrary layouts with 25 wind turbines.

Layout	Total power (kW)	Layout efficiency (%)	Capacity factor (%)
Layout 1	10,807	48.8	14.4
Layout 2	17,268	78.0	23.0
Layout 3	17,577	79.4	23.4
Layout 4	11,305	51.0	15.1
Layout 5	6,813	30.8	9.1
Layout 6	5,291	23.9	7.1

Table 2 summarizes the results of total output power, layout efficiency and capacity factor that were obtained for the six arbitrary layouts analyzed by the algorithm. The values in Tab. 2 may be compared with those from Tab.1, in which the layouts from Farias and Couto (2013) were analyzed, and it is possible to notice that the calculated efficiencies are low: the highest efficiency is that of layout 3, 79.4%, whereas the efficiencies in Tab. 1 are generally higher than 90%. This is due to the fact that those first layouts had been submitted to a computational optimization process, which means the use of algorithms also to optimize the arrays of wind turbines. Since the layouts of this paper were manually prepared, it is harder to obtain very high efficiencies. It can also be noticed that the capacity factors are very low, ranging from 7.1% to 23.4%. The reason for this is that the adopted average wind speed is 8.0 m/s, for which the power converted by the wind turbine is only 886 kW. That wind turbine would generate the rated power of 3,000 kW only with wind speeds about 15.0 m/s. If the algorithm were able to use variable wind speeds, measured over a year, for example, it would be possible to obtain more realistic analyses. Nevertheless, after the performed analyses, it was possible to verify the significance of the wake effect in wind farms and to confirm the utility of simple tools, such as the algorithm developed in this work, in preliminary wind farm projects.

5. CONCLUSIONS

The algorithm used in this work was developed in MATLAB with the purpose of evaluating the impact of wake effect on the power generation of a wind farm. Jensen wake model was selected to describe multiple wakes phenomenon. The algorithm performed a good operation and its results were compared to literature, what proved that the adopted mathematical model, despite its simplicity, can provide good results. Moreover, the algorithm itself proved to be useful as a tool to be applied to preliminary projects of wind farms. The analyzed layouts confirmed the great impact the wake effect has on energy production, layout efficiency and capacity factor of a cluster of wind turbines. The total generated power can be significantly increased or decreased without changing the number of turbines, only changing their positions. In consequence, efficiency and capacity factor are very affected.

Since the applicability of the software was proved, then it can be used in more complex and realistic situations. The work's objective of applying the algorithm to local characteristics of Rio Grande do Norte was achieved, by adopting an annual average wind speed and a surface roughness of the terrain taken from a location in the state. However, this is a very simple situation: constant speed and unidirectional wind. The algorithm can receive improvements, for example, to use time series of wind speed data annually measured. The analysis can be even more realistic by taking wind speeds measured *in loco* at the chosen location and observing the surface roughness from the local terrain, as well by using wind turbine models which are applied in real wind farms in that region. These ideas can be the starting point to perform new researches or to extend the research developed in this work.

6. ACKNOWLEDGEMENTS

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