Research Article

OPTIMIZATION OF WIND FARMS BY ADJUSTING THE PITCH ANGLE AND MINIMIZING WAKE EFFECTS

Abdelouahad Bellat[1], Khalifa Mansouri[2], Abdelhadi Raihani[3]

[1,2,3] SSDIA Laboratory, Hassan II University of Casablanca, ENSET of Mohammedia, 28830, Morocco
bellatabdelouahad@gmail, khmansouri@hotmail.com, abraihani@yahoo.fr

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ABSTRACT

Advances in the field of wind farm design are leading researchers to find the optimal design for the layout of wind turbines. The objective of this article is to study the optimization of the pitch angle of each wind turbine in order to maximize energy production and minimize the total investment cost in a wind farm. The reliable analytical gauss model including the effect of turbulence was chosen in our study, the genetic algorithm with a defined objective function, allowed to maximize and minimize the wake losses using the optimization of the angle pitch for each turbine. To validate our methodology, the off-rev1 wind farm was chosen in this study. The results obtained by applying this approach to a set of wind turbines have shown the importance of adjusting the pitch angle in the optimization of wind farms and minimization of wake effect.

Keywords: wind farm, optimization, pitch angle, genetic algorithm, wake effect.

1 INTRODUCTION

Renewable energies have become the best alternatives to other energies, a lot of effort has been made in recent years to reduce dependence on conventional energy sources. Wind energy is one of the most demanded energies which does not require any fuel, does not create greenhouse gases, does not produce toxic or radioactive waste. According to recent statistics, wind energy represents 14% of exploitation in the European (Union Wind Europe,2019), the World Wind Energy Association (WWEA) and Figure 1, show that the world demand for electricity has reached 6 % in the year 2018, However the wishes of wind turbine designers is to reach an installed capacity of 235 GW by 2030. Indeed, a lot of research has been done aimed at solving the problems related to the efficiency of the parks. wind farms (Qian et al,2021), (Gagliardi, F,2010), in other studies the authors (Adaramola et al,2011), have tried to develop a maintenance strategy to maximize the production of a wind farm with minimal cost, wake effects and losses. induced by this phenomenon has been studied extensively in literature (Akay, B. et al,2013), (Balasubramanian, K. *et al,* 2020), until today studies have shown the inability to suppress wake effects, on the other hand they can be minimized and standardized (Bellat, A. et al,2021).

Our study is focused on optimizing the pitch angle of wind turbines in a wind farm in order to maximize power and reduce the cost of installing wind turbines.

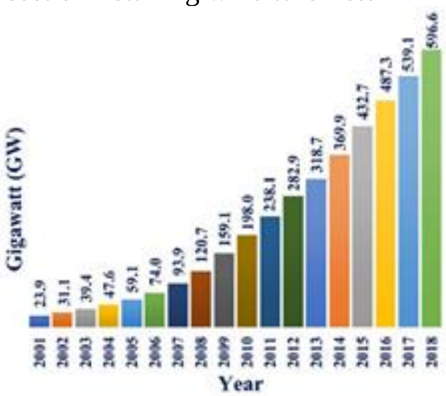

Figure 1: The cumulative wind capacity between 2001-2018, (Serrano González et al,2021)

Energy assessment is often based on analytical wake models. Unlike CFD (Computational Fluid Simulation) models which take a long time to calculate. In our study, the adoption of the analytical

wake model will allow us to evaluate a large amount of potential solution in an acceptable time. Indeed, many studies have adopted this model, the work of (Serrano González et al,2021). (Tian, J. et al,2017) used the analytical model and an objective function aimed at maximizing energy, (Hou, P et al,2016),developed the same objective function but with a particle swarm algorithm, the authors (Zhang, B. et al,2018) tried to criticize and improve the studies made by (Azlan, F. et al, 2021), other authors (Dilip, Det al, 2017) tried to study the effect of turbulence and awakening in the wind farm by the test on two aligned turbines and the adjustment of the pitch angles ,the Park model which has been adopted by authors (Deljouyi et al,2020) and (Ahmad, T. et al. ,2019), it is based on the intensity of turbulence and has the same objective function of maximizing power.
The aim of this article is to study the wake recovery induced by the intensity of turbulence of each wind turbine by exploiting the wake model of Bastankhah and Porté-Agel (Bastankhah, M et al,2014).The choice of this model is justified by the fact that it is close to the real results and simulation (Bastankhah, M et al,2014) and (Niayifar, A et al,2016).The objective function studied aims at maximizing the power and minimizing the cost in a wind farm, the parameter tested in this objective function is the pitch angle.
After this brief introduction, the rest of the paper is structured as follows: Section 2 presents the energy production model of the WF, by describing the proposed wake model and the operating conditions according to the pitch angle of the WT; Section 3 introduces the optimisation approach used to maximise the power captured by the entire offshore WF; Section 4 presents the results obtained in the proposed tests and, finally, Section 5 presents the conclusions of the work carried out.

2 WIND FARM MODELING

2.1 Wake Effect Model

The GAUSS model developed by Bastankhah and Porte-Agel (Bastankhah, M et al,2014).is based on the law of conservation of mass and the law of conservation of momentum. As shown in Figure2 the speed distribution is Gaussian, so the deficit of speed can be calculated in equation (1).

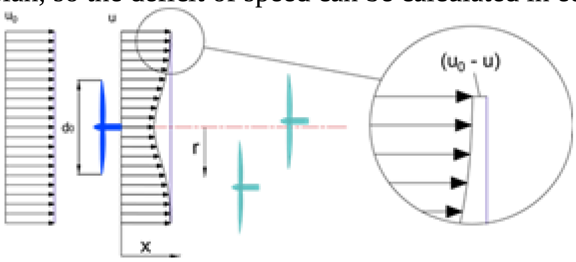

Figure 2: Gaussian distribution of speeds behind a wind turbine

$$\frac{\Delta U}{U_\infty} = \left(-\sqrt{1-\frac{C_T}{8(\sigma/d_0)^2}}\right).\exp\left(-\frac{1}{2(\sigma/d_0)^2}.\left\{\left(\frac{z-z_h}{d_0}\right)^2+\left(\frac{y}{d_0}\right)^2\right\}\right)$$

(1)

where,

- $\frac{\Delta U}{U_\infty}$: normalized speed deficit, defined as:

$$\frac{\Delta U}{U_\infty} = \frac{U_\infty - U_W}{U_\infty} \qquad (2)$$

U_∞ corresponds to the speed of the free flow and U_W corresponds to the speed of the wake.

- d_0 : turbine diameter.
- σ : standard deviation of the Gaussian-shaped velocity.

The relation between σ and d_0 is expressed in the equation (3).

$$\frac{\sigma}{d_0} = k^* \frac{x}{d_0} + \varepsilon \qquad (3)$$

x represents the distance downstream of the turbine and k depends on the evolution of the wake. ε and k are defined by (Niayifar, A et al,2016) by the equations (4), (5)

$$\varepsilon = 0.2\sqrt{\beta_{AD}} \qquad (4)$$

$$k^* = 0.3837\,.\,I + 0.003678 \qquad (5)$$

I : represents the turbulence of the flow induced in the turbines

The thrust coefficient C_T and β_{AD} are related by the equation (6) developed by Frandsen.

$$\beta_{AD} = \frac{1}{2}\frac{1+\sqrt{1-C_T}}{\sqrt{1-C_T}} \qquad (6)$$

- $z - z_h$ and y respectively represent the vertical and horizontal distance from the axis of the rotor.

Turbulence makes it more difficult for a wind turbine to recover kinetic energy from the wind. Likewise, turbulence increases the fatigue of the mechanical components of the wind turbine. In general, the solution is therefore to increase the height of the towers in order to prevent the turbulence generated near the ground from influencing the surface swept by the rotor. Figure 3 shows that the intensity of turbulence increases in $A_{overlap}$ (wake overlap zone). The equation (7) expresses this increase in turbulence in a wind farm composed of several wind turbines which interact with each other through the effects of wake produced by each of them.

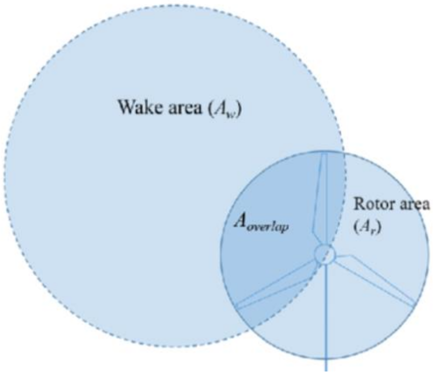

Figure 3: Partial and multiple wake effects

(Jensen, N. O., 1983)

$$I_{+,j} = \max\left(\frac{4A_w}{\pi d_0^2}\,.\,I_{+,kj}\right) \qquad (7)$$

$$\forall\, k = 1, \dots . N_t, k \neq j$$

$I_{+,j}$ expresses the increase in turbulence on the turbine positioned in position number j and affected by the k-th turbine.

2.1 Energy Calculation of a Wind Farm

The power produced by a turbine is a function of pitch angle β, power coefficient C_P , air density ρ , radius of the wind turbine R,wind speed u and speed ratio λ. its expression is noted in the equation (8).

$$P_{WT}(u, \beta, \lambda) = \frac{1}{2} C_P(\beta, \lambda)\rho\pi R^2 u^3 \qquad (8)$$

The equation (8) for energy production has been modified by (Abdulrahman, M,2019) and (Gao, X. *et al*, 2020), taking into account the effects of turbulence. thus, the new equation is noted below (9).

$$P_{WT}(u, \beta, \lambda, I) = P_{WT}(u, \beta, \lambda, I) \qquad (9) + \frac{1}{2}\frac{\partial^2 P_{WT}(u, \beta, \lambda)}{\partial u^2}\,.\,u^2 . I^2$$

We can finally conclude the final power of a wind farm which is the sum of the power of each turbine calculated in the equation (10).

$$P_{WF} = \sum_{i=1}^{N_t} P_{WT}\left(u_{W,i}, \beta_i, \lambda_i, I_i\right) \qquad (10)$$

Where,

$u_{W,i}$: real wind speed at the position of the i-th WT calculated considering the wake effect.

3 OPTIMIZATION METHODOLOGY

3.1 Objective Function

The objective function proposed in this article aims to maximize power through optimal pitch angles and minimize the cost of a wind farm by exploiting genetic algorithms in the calculation of the optimal objective function. The analytical model for the wake and the power coefficient resulting from the analytical equations allowed us to choose the meta-heuristic technique, hence the use of GA (genetic algorithm).

The objective function denoted by FOBJ is written as:

$$\mathrm{FOBJ} = \max\frac{\mathrm{P_{total}}}{\mathrm{Cost}} \qquad (11) = \max\frac{\sum_{i=1}^{N_t} P_{WTi}\left(u_{W,i}, \beta_i, \lambda_i, I_i\right)}{N\left[\frac{2}{3}+\frac{1}{3}e^{-0.00174N^2}\right]}$$

The cost relates only to the number of wind turbines installed (Sun, H. et al,2020) and (Tao, S. et al,2020). The individual / potential solution, is designated by X and which thus signifies the pitch angle assigned to the different wind turbines.

$$X = \left[\beta_1, \beta_2, \dots, \beta_{N_{t-1}}, \beta_{N_t}\right] \qquad (12)$$

Where,

$\beta_{WT}^{min} \leq \beta \leq \beta_{WT}^{max} \qquad \forall\, i = 1,2, \dots . N_t$

$P_{WTi} \leq P_{WT}^{max} \qquad \forall\, i = 1,2, \dots . N_t$

β_{WT}^{min} : minimum pitch angle

β_{WT}^{max} : maximum pitch angle

P_{WT}^{max}: rated power

3.2 Optimization Algorithm

The flowchart in Figure 4 details the optimization process for the wind farm studied. The data and models established previously will be used in a genetic algorithm (Serrano González et al,2018) and (Sahragard, A. *et al*, *2020*) whose steps are explained below.

- *Step 1*: Initially, we must generate an initial population which must be sufficiently diverse and large enough that the search can traverse the state space in a limited time.
- *Step 2*: Verification of the new arrangement of the wind turbines by the objective function.
- *Step 3*: The selection makes it possible to choose the individuals with whom the operations of reproduction will apply for the creation of the future generation. Subsequently, the cross is applied with two parents and generates two children.
- *Step 4*: New wind turbine layout established by the genetic algorithm (GA) and which leads to the modification of the previous generation. Several iterations will be tested until reaching the maximum iteration.

3.3 Case Study: Horns Rev Offshore

The Horns Rev wind farm was built in 2002 and is located in the North Sea, some 14 to 20 km from the coast of Jutland. it has 80 Vestas 2 MW wind turbines with a total power of 160 MW. The turbines are arranged in 8 rows and 10 columns with a distance of 7D between each two wind turbines, the dominant wind direction is considered (0 °). The table 1 summarizes the information of the studied wind farm.

Table 1: Horns -Rev wind farm information.

Site roughness	Mean wind speed	Wind direction	Wake decay coefficient	Air density
0.001	10.6	0	0.04	1.225

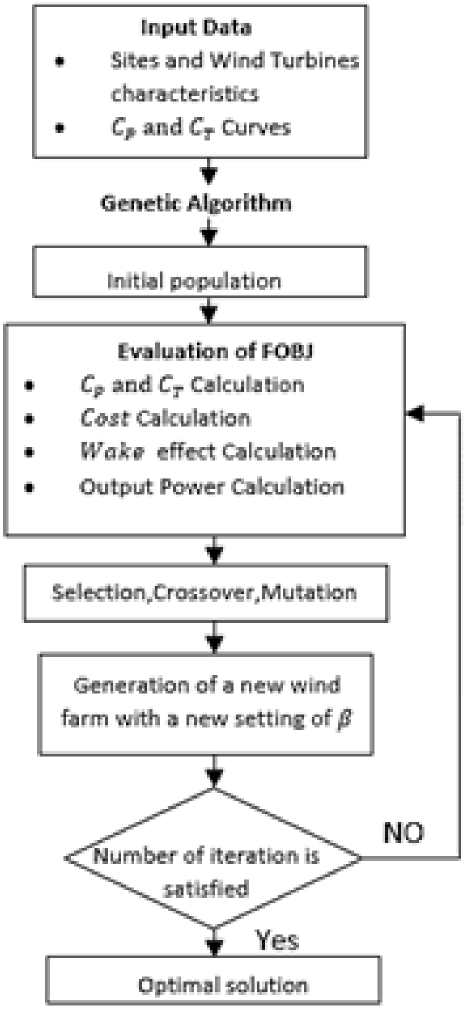

Figure 4: Steps to follow in the optimization

4 RESULTS AND DISCUSSION

The nominal operation of the turbines is generally dependent on the power coefficient, but it should also be noted that we can obtain power curves as a function of the wind speeds and the various pitch angle settings, the cases of step angle studied in our article is for $\beta < 0°$ or $\beta \geq 0°$.

Figure 5: Optimization of the wind farm studied by finding the optimum pitch angle for each wind turbine

The classic method consists in assigning 0 ° for the pitch angles to each wind turbine, this induces a maximization of the power. The results obtained during an optimization of the pitch angles are illustrated in Figure 5, the numbers in blue show the optimized pitch angle of each wind turbine. For many instigated between the old approach and the optimization method retained in this article, as indicated in figures 6 and 7 representing respectively the power produced for each wind turbine by the classical method and our optimal method by the choice of the optimal step angle. We can clearly see from Figure 6 that the power in the first column exceeds the value obtained by our optimization algorithm. is quickly caught in the second column as shown in Figure 7. This improvement which is worth about 10.3% is explained by the compensation due to the air flow disturbed by the effect of the upstream wakes.

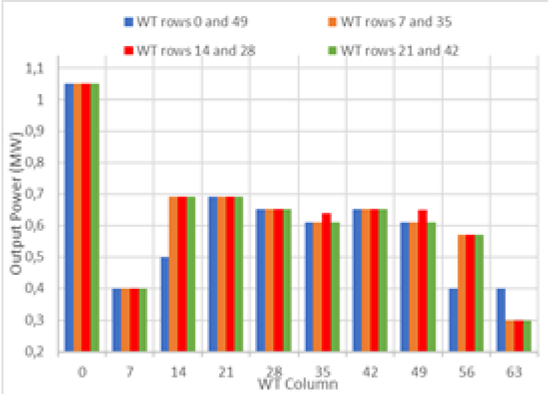

Figure 6: Power produced by wind turbines in the non-optimized case

We also note that the value of the power produced in rows 0 and 49 is the same, and the same case for rows 14 and 28, these results can be explained by the fact that the direction of the wind is perpendicular to the arrangement of the columns of the turbines following the middle row 21, which makes the speed field symmetrical in the other rows.

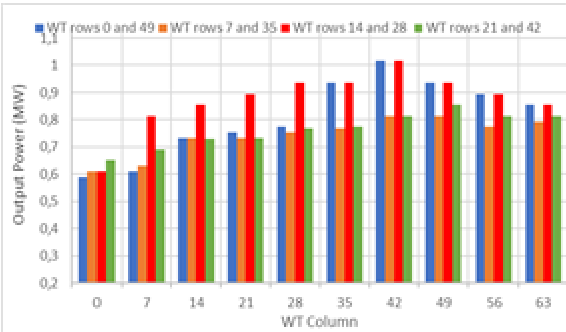

Figure 7: Power produced by wind turbines in the optimized case

The intensity of turbulence is an important factor in maximizing the power of each turbine, Figure 8 shows the variation of the intensity of turbulence in the classic case and in the optimized case, we can notice in the optimized case that the turbines located just after the column "0" operate with a higher intensity than the upstream turbines. This has an impact on increasing the wind speed along the wake and minimizing the loss of speed due to the wake. It should also be specified that the approach adopted by the optimization is to make the pitch angles $\beta \geq 0$ °.

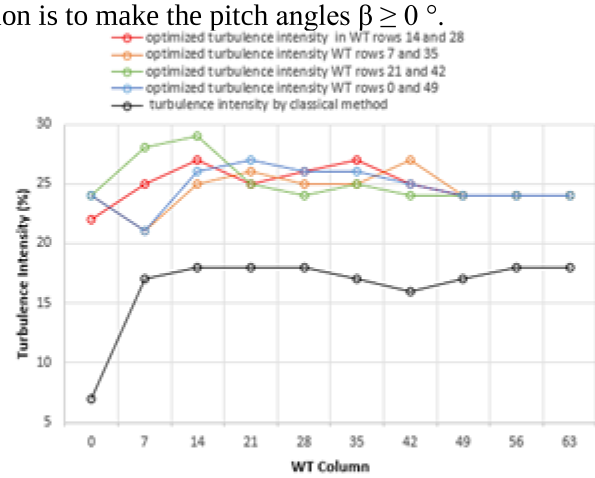

Figure 8: Intensity of the turbulence by the classical method and the optimized method

Figure 8 shows that the turbines in column "0" all operate with a negative pitch angle value, therefore with a power output lower than the rated power for the average wind speed, in the columns "7,14, 21 "the last columns take the value ($\beta = 0$ °) for its pitch angles. so, they operate at maximum power.

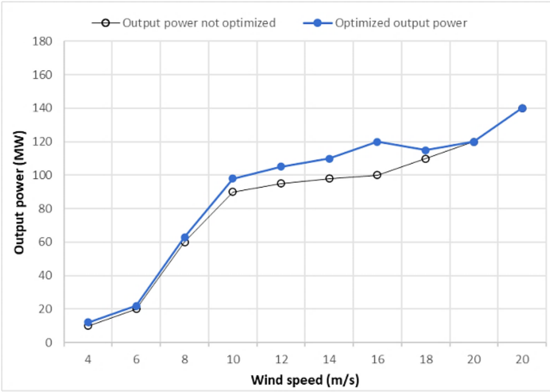

Figure 9: Variation of the sensitivity according to the speed of the incoming wind.

A sensitivity analysis for evaluating the approach used in our article is shown in Figure 9. As can be seen the optimization proposed by the genetic algorithm to allows to increase the power in the speed range of engagement and 16m / s, on the other hand for high speeds the energy production is the same because all the turbines operate at nominal power.

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It can be noted that in the speed range equal to or less than 10m / s the increase in output power follows a cubic shape, while in the speed range between

11m / s and 16m / s this increase does not follow. a cubic trend, this is due to the fact that the majority of wind turbines operate in the transition zone which the output power lower than that which would correspond to the power curve without turbulence.

5 CONCLUSIONS

In this article we tried to introduce an optimization method by controlling the pitch angles and minimizing the cost based on the Gaussian wake model proposed by Bastankhah and Porté-Agel. We also tried to exploit the turbulence effect which makes it possible to recover speed losses in the wake zone.

The results of this article have shown that the new approach using a genetic algorithm allows to increase the power of a wind farm by acting on the pitch angle of each wind turbine by exploiting the added turbulence and its effect on the recovery of speed.

It is also pointed out that the genetic algorithm used in this study gives better results for different values of speed and intensity of turbulence.

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