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OPTIMIZATION OF WIND FARMS BY THE PARTICLE SWARM ALGORITHM CONSIDERING GAUSSIAN WAKE MODEL

A. Bellat * I. Tyass Kh. Mansouri A. Raihani

Laboratory of SSDIA, Higher Normal School of Technical Education, Hassan II University of Casablanca, Mohammedia, Morocco
bellatabdelouahad@gmail.com, tyass1@yahoo.fr, khmansouri@hotmail.com, abraihani@yahoo.fr
**. Corresponding Author*

Abstract- The entire energy production of a wind farm may be increased by intelligently installing wind turbines in the correct place. This study presents a three-step technique for solving the Wind Farm Layout Optimization (WFLO) problem, with particle swarm optimization as the primary approach and the Gauss wake model. To provide a highly efficient optimum output power, the suggested technique is applied to a certain WFLO. To establish the non-wake and wake impacts at different levels, three case scenarios are explored. The optimization of the particle swarm is used to find the suitable locations of the wind turbines inside the wind farm. Wind turbine spacing is calculated using a rule of thumb. The proposed three-step technique is confirmed by the results of the MATLAB simulation. In addition, the results are compared with those of previous studies, demonstrating that the suggested optimization technique produces a good suggestion based on total output power generation and efficiency. Using a minimized objective function with a new cost expression and a power which is expressed as a function of the pitch angle, the simulation results indicate that the proposed technique is dependable in the WFLO architecture since it consequently optimizes the goal function by looking for the optimal wind turbine layout with the optimal pitch angle.

Keywords: Wind Farms, Optimization, Particle Swarm, Cost, Pitch Angle.

1. INTRODUCTION

Wind energy is becoming a more cost-effective source of power, not just when compared to other renewable sources of energy, but also when notably in contrast to traditional fossil fuels [1]. By the end of 2017, the total installed wind capacity in the world had surpassed 539 GW [2]. Wind power accounts for around 6% of worldwide electrical capacity and more than 3% of total world electricity output [3-4]. Wind energy capacity accounts for more than half of worldwide renewable installed capacity (excluding hydropower) [1], as well as more than half of the growth [5]. Wind is also the fastest developing energy source (after photovoltaic cells) [1-5].

Multiple turbine wakes cause considerable wake-turbine and wake-wake interactions in the wind farm, reducing overall energy output and increasing turbulence severity. Wind farm control's potential decrease wake losses by organizing specific pitch or yaw control actions across wind turbines has been researched for more than a decade [6]. Higher power output, reduced turbine loads, and power grid support services are the major goals of wind farm control, with increased energy output viewed as the most major advantages [7].

The usage of WTs with the same characteristics is widely recommended by system designers because to its practicality and cheap operating cost. [8-9] addressed the first WFLO issue, which was to identify the number and placement of WTs necessary at a particular area. In three distinct situations of wind speeds and directions, the authors optimized the number of wind turbines necessary for a particular plot of land. [10] made a significant contribution. In these trials, GA was used to gently alter the optimization parameter values. The WTs' ideal placements were much better after the changes. The authors of [11] suggested that wind farm limits be increased from 2Km×2Km to 2Km×2.2Km, similar to those in [9, 10, 12]. For this investigation, three case situations were used.

The findings revealed that utilizing the micro siting approach and GA, the WFLO issue could be solved reasonably well. Boundaries limited these optimization approaches, and a WT could only be placed in the middle of a single cell. In [13], a geometric pattern-based technique was used to place the WTs for the purpose of optimizing the wind farm's overall output power and overcome the solution space's sub-optimality. The strategy was successfully implemented. The available wind farm space for grid-based turbine deployment, on the other hand, was not fully used. The tremendously important wake effects were once again underestimated.

More algorithms have been developed to expand the mobility range of WTs inside a particular geographical region. A biogeography-based optimization approach was used in [14] for a circular wind farm to arrange the WTs with a restricted rotor diameter and inside the boundary to optimize the predicted output energy. The large correlation complexity constantly impairs the computational efficiency in instances when several parameters are needed for optimization. A standard wind farm was optimized in [15] by taking into account three factors: the wind farm's placement direction, the spacing of each pair of WTs, and the wind farm's control approach.

To boost the chances of obtaining the global optimum, an adaptive particle swarm optimization (PSO) [16, 17, 18] was used for WT layout optimization. Because of the proper placement of the WTs, the optimal trade-off between energy returns and capital expenditures is achieved. With all of these accomplishments, the control strategy's accuracy is solely dependent on the wake model's accuracy in predicting wind speed at each WT. Using the PSO method, a multi-objective function was introduced in [19] to reduce the layout cost while maximizing the energy production.

Despite its excellent execution, the wind farm's wake impact and discounted cost through its life cycle were not taken into account. A PSO with several adaptive approaches was also developed in [20] to capture more maximum output power. Some restricted zones were used without enough consideration of the WT spacing. With the effective application of PSO, if extra layout considerations are taken and the wake effect is managed in accordance with the rule of thumb, an efficient position for the optimum output power will be attained in any constrained wind farm site. As a result, a three-step technique for minimizing the objective function is given.

2. WIND FARM MODELING

2.1. Gauss Wake Model

The wake effect phenomenon modifies the speed of the wind as it passes through upstream Wind turbines (WT). Growing impacts are seen in the windiest location by a decrease in wind speed and an increase in turbulence. In fact, as compared to upstream WT, turbines in the wake area produce the least electricity and require more maintenance. As a result, wake effect modeling may be useful in deciding where WT should be placed. It also should be considered in optimizing the layout of a wind farm (WFDLO).

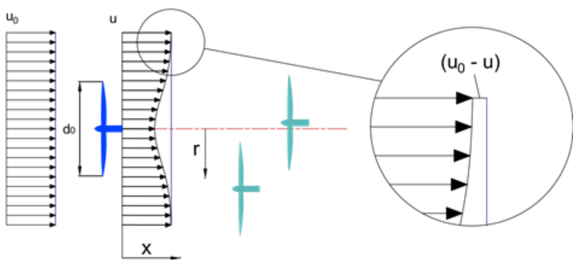

Figure 1. Gaussian distribution of speeds behind a wind turbine [26]

The two wake models (analytical and computational), which are at the heart of the resolution of the Navier-Stokes equations and are reliable than the other models, are the two primary kinds. They do, however, need greater calculation and expense, rendering their usage in WFDLO difficult [23]. Analytical wake models, on the other hand, are based on analytical wind speed solutions, which are commonly utilized in optimization approaches, notably for big WFs with a large amount of WTs [24-25]. In this study we will work with the Gauss model developed by Bastankhah and Porte Agel [26]. It is based on the conservation of the laws of mass and momentum, as well as on the conservation of the law of energy. Since the speed distribution is Gaussian, the choice of this model is justified by the fact that it is close to the real and simulation results. Figure 1 shows the speed deficit which can be calculated using equation (1).

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

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

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

where, U_∞ corresponds to the speed of the free flow, U_W corresponds to the speed of the wake, d_0 is turbine diameter, and MW is standard deviation of the Gaussian-shaped velocity.

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

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

The distance downstream of the turbine is represented by X, while the development of the wake is represented by k^*. The variables ε and k^* are defined by [27] using the equations (4) and (5), respectively.

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

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

where, I is represents the turbulence of the flow induced in the turbines.

The relationship between the thrust coefficient C_T and β_{AD} is represented by the equation (6) established by Frandsen.

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

- where, $Z-Z_h$ and y indicate the vertical and horizontal distances between the rotor's axis and their corresponding values.

2.2. Modeling of Energy Production

The power generated by a wind turbine is a function of the pitch angle β, the power coefficient C_P, the air density ρ, the radius of the wind turbine R, the wind speed u, and the speed ratio λ. The expression for it is given in the equation (7).

$$P_{WT}(u,\beta,\lambda)=\frac{1}{2}C_p(\beta,\lambda)\rho\pi R^2u^3 \quad (7)$$

To account for the impacts of turbulence, equation (8) for energy production has been modified by [28, 29], accordingly, the new equation (8) is presented as follows:

$$P_{WT}(u,\beta,\lambda,I) = P_{WT}(u,\beta,\lambda) + \frac{1}{2}\frac{\partial^2 P_{WT}(u,\beta,\lambda)}{\partial u^2}.u^2.I^2 \quad (8)$$

Finally, we may compute the total power of a WF, which is equal to the sum of the power of each turbine determined in the following equations (9).

$$P_{WF} = \sum_{i=1}^{N_t} P_{WT}(u_{w,i},\beta_i,\lambda_i,I_i) \quad (9)$$

where, $u_{w,i}$ is real wind speed at the position of the ith WT calculated considering the wake effect.

The efficiency of the WF is calculated using the following formula:

$$\eta_{WF} = \frac{P_{WF}}{(\frac{1}{2}\rho\pi\frac{D^2}{4}C_{EF}V_f^{\,3})} \quad (10)$$

2.3. Simple Wind Turbine Model

Figure 2 illustrate the power graph of a typical wind turbine. In various wind speed zones, the single wind turbine power output P_{WT} is given by equation (11).

$$\begin{cases} 0 & v<3 \text{ m/s or } v<25 \text{ m/s} \\ 0.3v^3 & 3 \text{ m/s} \le v < 12 \text{ m/s} \\ 518.4 \text{ kW} & 12 \text{ m/s} \le v \le 25 \text{ m/s} \end{cases} \quad (11)$$

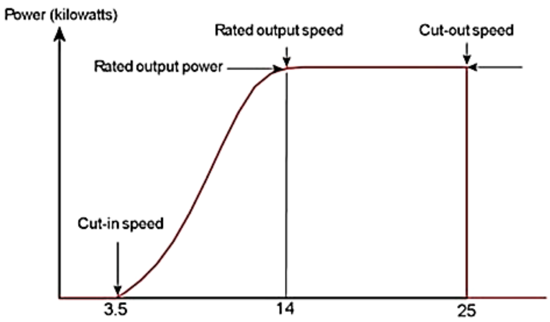

Figure 2. Classic WT power graph [31]

The wind farm's total annual energy output AEP is determined as follows:

$$AEP = 8760 P_{WF} \quad (12)$$

2.4. Modeling the Cost of Installing WT in a WF

During the creation of any power plant, the primary aim is to produce electricity at the optimum cost. During the development of any power plant, the fundamental objective is to produce energy at the lowest practicable cost. On a physical level, cost estimation is among the most difficult elements of the WF design process. The simple normalized model presented by Mosetti et al. [30] was employed in the bulk of papers published during the WFDLO period. It considers that the cost of WF is just a function of the number of WTs. Because it does not include the many factors related to a WT's configuration, such as rotor radius, hub height, and rated power, utilizing such a model to determine WF cost with various WT variants.

We suggest in this study to relate the cost of WF to the cost of WT in order to more correctly forecast WF cost as a consequence of these design elements. This assumption is supported by the fact that WT costs are the most costly element of WF, accounting for around 44% of onshore farms and 64% of offshore farms [31]. As a result, we use the cost model given in reference [32], which consists of the sum of rotor-nacelle assembly (RNA) cost as a function of rated power and WT tower cost as a function of WT design factors. As a result, the WF cost may be expressed as [32]:

$$\mathrm{Cos}\,t = N\left(1170P_r + \left(1.5\left(0.016D^{2.8}\left(\frac{Z_h}{D}\right)^{1.7}\left(\frac{P_r}{A}\right)^{0.6}\right)\right)\right) \quad (13)$$

where,

p_r: Wind turbine rated power (MW)

N: Number of wind turbines

Z_h: Height of wind turbines (m)

A: Wind turbine sweeping area (m^2)

3. OPTIMIZATION PROCESS

3.1. Objective Function

The energy minimization cost is the objective function for WFLO optimization. As a result, the objective function is the ratio of total installation cost to P_{WF} produced.

The FOBJ objective function is calculated as follows:

$$FOBJ = \min\left(\frac{\mathrm{Cos}\,t}{P_{WF}}\right) =$$

$$= \max \frac{\sum_{i=1}^{N_t} P_{WTi}(u_{w,i},\beta_i,\lambda_i,I_i)}{N\left(1170P_r + \left(1.5\left(0.016D^{2.8}\left(\frac{Z_h}{D}\right)^{1.7}\left(\frac{P_r}{A}\right)^{0.6}\right)\right)\right)} \quad (14)$$

where,

$$\beta_{WT}^{\min} \le \beta \le \beta_{WT}^{\max} \quad , \quad \forall i = 1,2,....N_t$$

$\beta_{WT}^{\min}$: minimum pitch angle

$\beta_{WT}^{\max}$: maximum pitch angle

3.2. Optimization Algorithm

Prior to installation, the possibility of a preferred wind speed and WT location must be taken into account in a proper manner. [33] specifies the required WT spacing in a wind farm using the empirical rule. The wind, on the other hand, has its own set of probabilistic characteristics. They have a variety of speeds, densities, and directions, but they are most prevalent in one direction at a certain location. Regardless of the direction of the wind, a WFLO will provide a unique configuration that will either generate or not generate optimum output power.

Three research scenarios of wind speeds and directions for the WFLO are selected to test the reliability of the optimization method. From 0° to 350°, wind directions are split into 36 equal intervals. Each WT has the ability to spin in accordance with the prevailing wind directions.

The PSO algorithm was used to optimize the objective function studied using Jensen's model. The approach used in this study is based on three steps and that is to find the best position for the WT. This technique uses a sequential approach to achieve the objective function, which results in high energy output from the wind farm while reducing the impact of the wake. Three case studies, including constant wind speed and direction, constant wind speed with changing wind direction, and variable wind speed with changing wind direction, are also studied to ensure the reliability of the strategy.

The process starts with the WT specs, square wind farm size, terrain characteristics, wind scenario, wind speed, wind direction, number of WTs, PSO characteristics (functions/parameters), Jensen model data being entered.

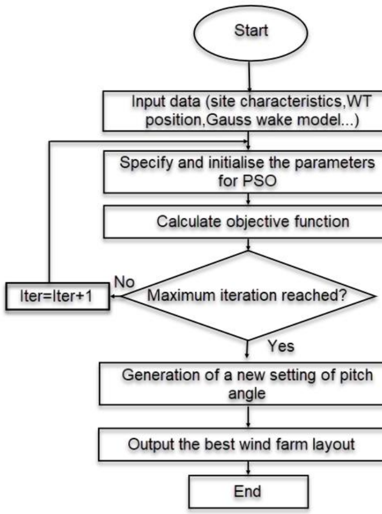

Figure 3. Flowchart of the optimization by the PSO algorithm

The WFLO is oriented north at 0 degrees (wind farm boundary 45 degrees to the x-axis), assuming this is the primary wind direction. The initial goal function is calculated after a number of WTs have been placed at random. In MATLAB, the PSO method is used to produce the next objective function, which is then compared to the previous one and updated as a new objective function. The Gauss model then checks the spacing between neighboring WTs after obtaining a higher objective function. This means that the process continues until you get the desired result. Figure 3 illustrates the PSO flowchart for obtaining the suggested WFLO.

In this research, As illustrated in Figure 4, we will divide the WFO into a number of cells to indicate the potential placements of the WTs.

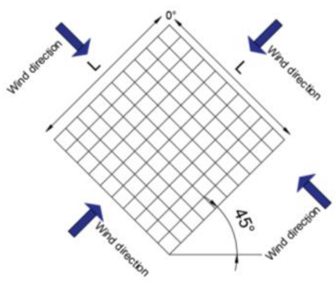

Figure 4. Wind farm border and wind directions of size $L \times L$ [10]

4. ANALYSIS OF STUDY RESULTS

4.1. Case Study 1: Constant Wind Direction and Speed

In this part, the wake effect and objective function are addressed in relation to the MATLAB simulation results for the proposed WFLO in the three case situations. The data requirements for all WTs in the wind farm are the same: $Z_0 = 0.3$m; $Z = 60$m ; $C_T = 0.88$; $D = 40$m, overall wind farm dimension chosen is 2km×2km. The wind farm is split into 100 WT locations or cells (200m×200m). The particle limitation parameters are inertia weight coefficient $W = 0.5$, acceleration coefficient constants $C_1 = 2.5$, $C_2 = 2.5$, and the maximum number of iterations $Iter_{\max} = 100$, and the PSO settings are utilized for the fast response.

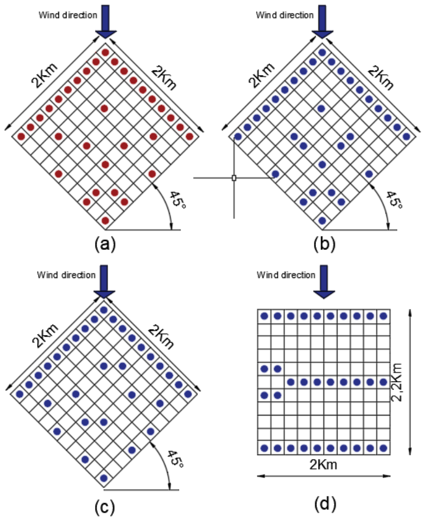

Figure 5. Case study results, (a) WFLO of the suggested approach, (b) WFLO of [10], (c) WFLO of [12], (d) WFLO of [11]

The WFLO is studied in this case with a constant wind speed of 12 m/s and a fixed north wind direction (0°). The optimized wind farm is shown in Figure 5 (a) after full implementation of the proposed three-step approach, and it is compared to those of [10, 11, 12]. The distance between neighboring WTs is more than the minimal rule of thumb. As a result, the neighboring WTs are not taken into consideration in the equation since their vertical spacing is much greater. As a result of the approach, the wake impact on downstream WTs is minimized, allowing for higher power output.

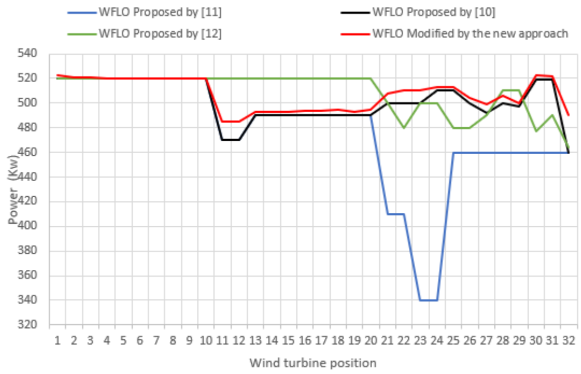

Figure 6. WT output power at different locations

Figure 6 indicates that the first 10 WTs of the WFLO of [11] generated the highest output power; after that, the output power of remaining 22 WTs starts to decline. The wind farm's lowest production power was 345.2514 kW. WFLO's overall performance is summarized in Table 1.

Table 1. Result of case study 1

Optimization strategy	WFLO by new approach	WFLO of [12]	WFLO of [11]	WFLO of [10]
N_t	32	32	32	32
Total power (kw)	16927.47	16251.56	15218.20	16326.59
Wake loss (Kw)	245.54	337.24	1370.60	262.20
AEP (MWh)	145060.25	142363.67	133311.4	143020.98
Objective	0.00139	0.00154	0.00155	0.00140
Efficiency (%)	98.97	97.77	91.74	98.42

The decrease in power output in [12] began after the first 19 WTs. The remaining WTs had just a little impact on the downstream WTs. The lowest WT output power reported was 465.25 kW. Although the suggested WFLO's power output started to decrease after the first 19 WTs, its resilience stayed the same for the last 13 WTs. All of the WTs produced a considerable amount of power. We also observe that the power of the final turbine has increased significantly since the research by [10].

With an objective function of 0.00155, [11] achieved an efficiency of 91.74% using the WFLO's goal function. The in-limit wake effect had a detrimental impact on more than two-thirds of the WTs. In WFLO of [12], a 97.77% efficiency was obtained. The revised GA optimization method significantly decreased the wake effect, resulting in an objective function of 0.001537. [10] created a method that was able to reach a 98.42% efficiency rate. Regarding the WFLO provided by our method, which is based on the same objective function but with a different representation of the cost to increase efficiency, 98.97%.

4.2 Case Study 2: Constant Wind Speed and Variable Wind Direction

In this case, a scenario with an unchangeable wind speed and a variable wind direction is studied. The average wind speed used in this case is 12 m/s, with equal chances of wind coming from all directions. All of the WTs are inside the wind farm and may rotate in response to changing wind directions. The WFLO has several layout patterns that correlate to the wind speed at every angle of the wind direction. The method solved all of the cases for one wind direction fast using the suggested approach. As additional wind directions were added, however, certain cases were not handled optimally. A solution was found after a large number of iterations, and the optimum WFLO produced more output power. As a result, the suggested approach was able to reduce the goal function even further. The best WFLO is shown in Figure 9 and is compared to those in [9, 21] (a). Table 2 compares the WFLO's overall performance to [9, 21, 10].

Because most of the WTs were aligned with some of the wind directions in [9, 10, 21], greater wake effects were detected. More than four WTs were aligned in certain instances. The majority of the WTs were located around the wind farm's perimeter. The three-step approach, on the other hand, resulted in a high output power. This was due to the evenly dispersed WTs causing a decreased wake effect. The goal function was decreased to 0.00161 with a 98.97% efficiency as a consequence.

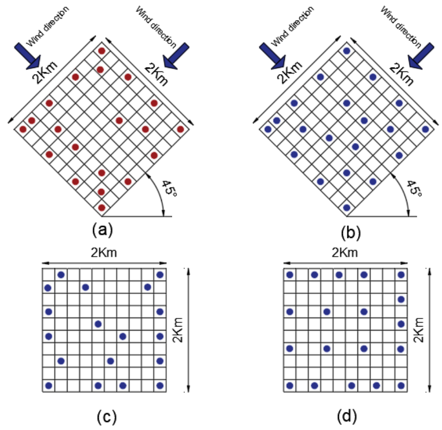

Figure 7. Case study results, (a) WFLO of the suggested approach, (b) WFLO of [10], (c) WFLO of [9], (d) WFLO of [21]

Table 2. Result of case study 2

Optimization strategy	WFLO by new approach	WFLO of [9]	WFLO of [21]	WFLO of [10]
N_t	19	19	19	19
Total power (kw)	9760.56	9549.00	9244.70	9741.30
Wake loss (Kw)	101.44	300.60	604.90	108.30
AEP (MWh)	85685.05	83649.24	80983.57	85333.79
Objective	0.00161	0.00168	0.00174	0.00164
Efficiency (%)	98.97	96.95	93.86	98.90

It should be noted that the objective function used in our approach is different than that used by [10], in our approach the cost is a function of several parameters namely the diameter the number of turbines the nominal power and others, on the other hand in the results obtained by the studies of [10], the cost is a function of a single parameter which is number of turbines, hence improvement of objective function, power and efficiency.

4.3 Case Study 2: Variable Wind Direction and Speed

The changing wind speed and direction in this case study are comparable to those in [10-9-34]. Between 270 and 350 degrees, high wind speeds are common. This case study is very identical to case study 2. As indicated, average wind speeds of 8, 12, and 17 m/s are utilized sequentially from the main wind directions. Figure 8 (a). The majority of the WTs are placed along the wind farm's borders, as illustrated in Figure 8, in the WFLOs of [9, 34]. Some, particularly those aligned with wind speed, were congested and adversely affected by the wake effect.

In this case study, the suggested approach comprised a well-designed uniform WFLO that took into consideration the potential of wind blowing from any direction. As a consequence, the wake effect was minimized, resulting in an optimum WFLO with a high efficiency of 99.0102 percent, which is slightly higher than [10]. According to Table 3, the three-step approach is capable of overcoming most of the issues identified in previous research with similar limitations [9, 11, 12, 34]. As a result, it shows that output power and efficiency have been enhanced, reducing the objective function.

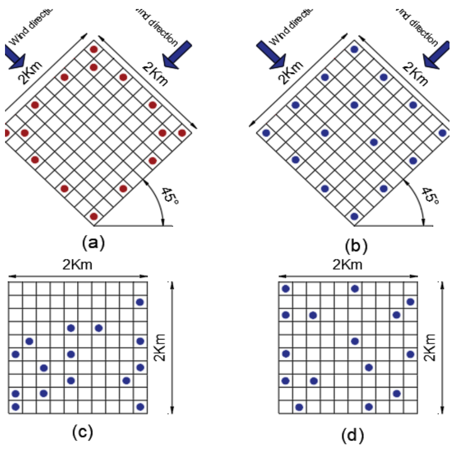

Figure 8. Case study results, (a) WFLO of the suggested approach, (b) WFLO of [10], (c) WFLO of [34], (d) WFLO of [9]

Table 3. Result of case study 3

Optimization strategy	WFLO by new approach	WFLO of [34]	WFLO of [9]	WFLO of [10]
N_t	15	15	15	15
Total power (kw)	15780.23	1470.00	13460.00	15020.78
Wake loss (Kw)	147.62	13717.50	1727.50	166.72
AEP (MWh)	1323421.27	12877.20	117909.60	131582.03
Objective	0.000872	0.000910	0.000994	0.000891
Efficiency (%)	99.01	97.16	94.62	98.90

5. CONCLUSION

A new three-step method to minimize the objective function of WFLO is described in this article. The cost expression for this study differs from what is commonly used in the literature. The first step is the diagonal design of the 2km×2km wind farm, which exposes a larger area to the wind. The PSO method is used in the second phase to determine the best locations for each WT, taking into account all potential wind speeds and optimum pitch angles while maintaining the required spacing between adjacent WTs. Finally, the Gauss model was used to study and determine the wake effects operating on the WTs in all locations, according to the rule of thumb.

The improved WFLO was evaluated in three wind speed and direction case studies. As a result, the location of each WT has been carefully chosen to maximize power output. The simulated results for the objective function were further reduced in the WFLO for all cases using the new method and an objective function which included a new expression of cost and power as a function of pitch angle. The potency and effectiveness were significantly better compared to the results of previous research. Loss and wear have been reduced by the suggested method, allowing the WT to achieve expected life due to minimized wake impact. Finally, if implemented, the approach should provide quick returns on investment as well as increased plant efficiency. This shows that the suggested three-step approach can result in an optimal WFLO.

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BIOGRAPHIES

Abdelouahad Bellat was born in Safi, Morocco in 1981. He is a Ph.D. student at ENSET Institute, University Hassan II Casablanca, Morocco since 2018. His research focuses on the design and optimization of wind farms using artificial intelligence algorithms.

Ilham Tyass was born in Mohammedia, Morocco in 1980. She is a Ph.D. student at ENSET Institute, University Hassan II Casablanca, Morocco since 2018. Her research focuses on optimization and numerical modeling of a hybrid wind-photovoltaic system with energy storage.

Khalifa Mansouri was born in Azilal, Morocco in 1968. He is now a teacher of computer science and researcher at ENSET Institute, University Hassan II Casablanca, Morocco. He received Diploma of ENSET Mohammedia in 1991, CEA in 1992 and Ph.D. (Calculation and optimization of structures) in 1994 from Mohammed V University in Rabat, Morocco, HDRin 2010and Ph.D. (Computer Science) in 2016 to Hassan II University in Casablanca, Morocco. His research is focused on real time systems, information systems, e-learning systems, industrial systems (modeling, optimization, and numerical computing).

Abdelhadi Raihani was born in El Jadida, Morocco in 1968. He is now a teacher of electronics engineering and researcher at ENSET Institute, Hassan II University of Casablanca, Mohammedia, Morocco. He received the B.Sc. degree in Electronics in 1987 and the M.Sc. degree in Applied Electronics from ENSET Institute in 1991. He has his DEA diploma in information processing from the Ben M'sik University of Casablanca, Morocco in 1994. He received the Ph.D. in Parallel Architectures Application and image processing from Ain Chok University of Casablanca, Morocco in 1998. His research is focused on medical image processing and electrical systems related to wind and solar energy. He has published more than 30 publications in various National, International conference proceedings and Journals.