Indian Journal of Science and Technology, *Vol 8(17), DOI: 10.17485/ijst/2015/v8i17/69817, August 2015*

ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

The Modelling of Wind Farm Layout Optimization for the Reduction of Wake Losses

Rabia Shakoor[1] , Mohammad Yusri Hassan[1,2*], Abdur Raheem[1,3] and Nadia Rasheed[3]

[1]Centre of Electrical Energy Systems (CEES), Institute of Future Energy, Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Johor, Malaysia
[2]Faculty of Electrical Engineering, Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Johor, Malaysia; yusrih@fke.utm.my
[3]University College of Engineering and Technology, The Islamia University of Bahawalpur, Bahawalpur - 63100 Pakistan

Abstract

The objective of the present research is to find out the optimized dimensions of the wind farm area and turbines layout to reduce the overall cost per unit power. The velocity deficits caused by the wakes of each turbine were calculated by using Jensen's wake model. The optimal positions of wind turbine placement are evaluated by using genetic algorithm, while sustaining the obligatory space between adjacent turbines for operation safety. The research on the wind farm area dimensions and fully utilization of upstream wind velocity is currently lacking in literature. The logical application of area dimensions and genetic algorithm improved the overall efficiency of the wind farm. It is concluded that proposed duel level optimization method outperforms the existing ones. The total wind farm area ($2km \times 2km$) was divided into 100 identical cells, with each cell having dimensions $200m \times 200m$. The performance of the proposed method is compared with the results from previous studies. The simulation results showed that power output of the wind farm was increased by using same area with different dimensions. It was observed that by using the same number of wind turbines, the total efficiency of wind farm was increased by 7 %.

Keywords: Jensen's Wake Mode, Layout Optimization, Wind Farm Area Dimensions, Wake Losses, Wind Turbine Positioning

1. Introduction

Renewable energy system is an environment friendly, consistent and economical system that remarkably employs the local means. All types of sustainable energy systems (i.e., ocean, geothermal, solar, wind, hydroelectric, and biomass energy) have their own specific benefits that make them distinctively suitable for specific applications[1].

The installation demand of wind energy and the related research activities has experienced a tremendous increase in the past decade[2]. The Global Wind Energy Council Report[3] stated that wind energy has become the most rapidly rising source of energy in the world, having a steep increase in development from 2009. Such prompt expansion of the wind energy industry has led to many challenges for reduction the cost of producing power.

The fundamental task of a wind turbine is to extract the kinetic energy from wind and converting it into mechanical energy at the rotor axis, and then the conversion of mechanical energy into electrical energy[4,5]. In the primary process, when wind turbines extract the energy from wind, the rotation of wind turbine rotor can reduced the wind speed behind it and swirls the air flow, which is known as 'Wake Effect' of wind turbine. Because of this effect, the area behind the wind turbine is experienced a modified wind flow both in terms of mean velocity and turbulence intensity. There have been several models developed aiming for a better understanding on wake

---

**Author for correspondence*

dynamics. These can be divided into two main categories, namely analytical/explicit wake models[6–9] and computational/implicit wake models[10,11].

The world is moving towards the construction of wind farms comprising of many wind turbines instead of single wind turbine. Modern wind farms consist of tens of wind turbines arranged on the sites for the purpose of maximum utilization of wind energy. As the size and the number of turbines increases in wind farm, the cost will also increase. Thus, the main challenge is to reduce the cost per unit power of the wind farm[12]. The cost of wind farm depends on the number of factors, for example, the site layout design, the site selection, predictive maintenance, and optimal control system design. However, the aerodynamic behavior of wind turbines will generate large scale wakes in the downwind field, while excessive wind disturbance leads to low energy production in wind farms, and high turbulence intensities lead to high level of velocity fluctuation[13]. Therefore, it is very important to optimize the wind turbine positions in the wind farm to reduce the uncertainty in power output[14,15].

There are several researchers that addressed the wind farm layout optimization in the literature[16–21]. Mosetti et al.[16] used a discretized solution space in the wind farm area to optimize wind turbines location. The wind turbine wake effect calculation has been done by using Jensen's analytical wake model[6]. The genetic algorithm in which each row of the grid considered as a binary string is utilized for wind turbine positioning. The framework developed in[16] has been continuously used for comparison purposes in the proceeding research, including the wind scenario, the use of the Jensen's wake model, and objective function. Grady et al.[17].attempted similar but improved approach of genetic algorithm which integrated heuristic knowledge about the layout of wind farms for power optimization. Grady et al.[17] showed that the results obtained by Mosetti et al.'s were not optimum. They suggested that the probable cause, that the solution was not allowed to evolve for sufficient generations (i.e., it was not converged to the optimum point).

Marmidis et al.[18] also attempted the same wind farm layout optimization by Grady et al.[17] for analyzing constant direction and speed of wind. They used the Monte Carlo algorithm for optimization; however, description on their method was not given. Mittal[19] recommended the use of micro siting technique with Genetic Algorithm (GA) in order to find more precise locations of turbines inside a wind farm. He simulates the wind farm layout for three scenarios and proposed the increased size of wind farm equal to $2km \times 2.2km$ rather than $2km \times 2km$ as used in[16,17]. The spacing between the positions of wind turbines reduced by using condense grid size with each cell dimensions equal to $1m \times 1m$. The reduction of grid spacing resulted in the decrease of overall cost per unit power of wind farm. The reference[19] compared the obtained results with the results from the studies by Grady et al.[17]and Mosetti et al.[16] for all three wind scenarios.

Emami et al.[22] proposes an improvement in wind farm layout optimization with the Jansens's wake model by modification of the objective function, which takes into account the efficiency of wind turbines and the wind farm deployment cost. Reference[22] show that this amendment leads to improved results than earlier methods. Samina et al.[23] employ the genetic algorithm and spread sheet to solved the same wind farm layout optimization problem. In reference[24], the authors studied the influence of the wind turbines with different hub heights (50 m to 78 m) on the power production of a wind farm. Chen et al.[24] found that the wind farm wake losses can be minimize and power output became better by installation of varying hub heights wind turbines. Turner et al.[25] assuming a flat terrain for wind farm and develop a quadratic integer program and a mixed integer linear program for layout optimization.

The literature review gives a clear vision that mostly research in the field of wind farm layout optimization focused only on the wind turbine positioning within the specific area of wind farm[26]. However the research on the wind farm area dimensions and fully utilization of upstream wind velocity is currently lacking in literature. The present research proposes a method to obtained the best wind farm area dimensions (maximum width of area was become perpendicular to the dominant wind direction) for the given wind scenario. After that, the first 19 grid cells are filled by installation of wind turbines to utilize the all available free-stream wind velocity while satisfying the necessary distance between the wind turbines. The placement of the remaining wind turbines has been done by using the genetic algorithm[27] in the continuing portion of the wind farm. For validation, the obtained results in present study had been compared to the results of related previous studies.

The remaining parts of this paper are arranged as follows: Section 2 describes the proposed design models of the wind farm. Section 3 describes optimization steps. Section 4 presents the obtained results and gives a comparison with previous research. Finally, Section 5 presents the conclusion.

2. Wind Farm Modeling

This section describes power, cost and wake models of the wind farm proposed in present research work. These models are based on some assumptions which also given in detail.

2.1 Power Model

Available power in wind farm for each turbine can be estimated by using follows equation:

$$P_p = \eta \frac{1}{2} \rho A u_o{}^3 C_p \tag{1}$$

where P_p is the electrical power produced (W), η is the overall efficiency of the wind turbine, ρ is air density (kg/m^3), A is swept area of wind turbine (m^2), u_o is the free stream wind velocity (m/s), and C_p is the power coefficient, its value will be given as;

$$C_p = \frac{P_A}{\left(\frac{1}{2}\right) \rho A u_o{}^3} \tag{2}$$

Where P_A represents the aerodynamic power output of a wind turbine. In present study, by assuming that the wind turbine efficiency η is 40 %, the wind turbine produced power can be calculated as:

$$P_p = \frac{40}{100} \times \frac{1}{2} \times 1.2 \times \pi \times 20^2 \times u_o{}^3 kW \tag{3}$$

$$P_p = 0.3 \times u_0{}^3 kW \tag{4}$$

The above equation shows that the produced power is directly proportional to the cube of available wind velocity at the position of wind turbine. Therefore, in a wind farm the wind turbines facing free-stream velocity will give the maximum power output, however the downstream wind turbines will give the reduced power output because of the wake effect of upstream wind turbines. To determine the produced power from a wind turbine, it should be ensured whether the wind turbine under consideration lies in the wake of other wind turbine or not.

2.2 Wake Model

The calculation of the reduced wind speed from each wind turbine has been done by using an alytical wake model proposed by N.O. Jensen, which is based on the law of conservation of momentum[6]. The near field behind the wind turbine is neglected, making it possible to model the resulting wake as a negative jet. The mostly research in wind farm layout optimization used Jensen's wake model, because of its accuracy of results. The velocity deficit (u_d) in the wake of a wind turbine can be given as the fractional reduction of free-stream wind velocity.

$$u = u_o \left[1 - u_d\right] \tag{5}$$

The radius of the wake just behind the wind turbine will be equal to the radius of the wind turbine rotor. Figure 1 shows the wake effect of a wind turbine facing wind speed u_o . The wake radius r_1 depends on the down-stream distance, x, and increases linearly, as the wake propagates downstream. The downstream wind speed due to the wake effect of a single wind turbine is given by following equation,

$$u = u_0 \left[1 - \frac{2a}{1 + \left(\frac{\alpha x}{r_1} \right)^2} \right] \tag{6}$$

The induction factor, α, can be calculated from thrust coefficient , C_T of the wind turbine, $C_T = 4\alpha(1\text{-}\alpha)$. The,$\alpha$, in above equation is known as entrainment constant and defined as rate of wake expansion. The value of, α, is empirically given by equation.

$$a = \frac{0.5}{\ln\left(\frac{H}{z_0}\right)} \tag{7}$$

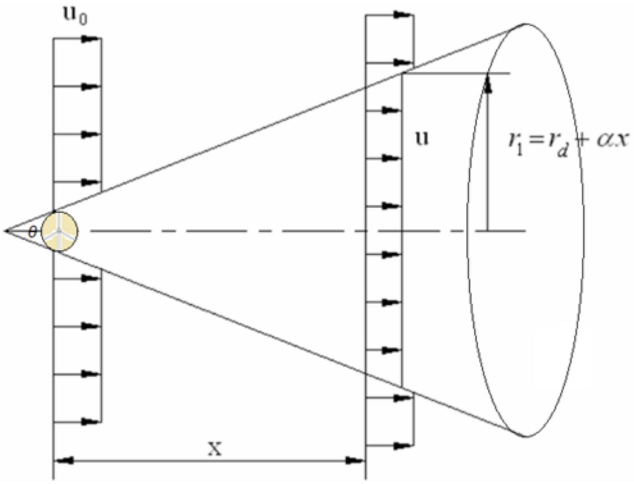

Figure 1. Wake behind a wind turbine.

Where, H, is the wind turbine's hub height and, z_0, represents the surface roughness of wind farm area. For present study it is 0.3 m.

The wake radius just behind the wind turbine, r_d, is called the downstream radius of the turbine. It can be determine by using equation 8, where, r_r, is the radius of wind turbine.

$$r_d = r_r\sqrt{\frac{1-a}{1-2a}} \tag{8}$$

The radius of wake at any distance, x, from a wind turbine is directly depends upon the value of r_d and entrainment constant , α , as given in following equation.

$$r_1 = r_d + \alpha x \tag{9}$$

In a wind farm when a number of wakes occurs together, the resultant velocity u_i can be calculated by equating the sum of the kinetic energy deficits of each wake to the kinetic energy deficits of the mixed wake at that point , as given in the following equations;

$$\left(1-\frac{u_i}{u_0}\right)^2 = \sum_{i=1}^{N_t}\left(1-\frac{u}{u_0}\right)^2 \tag{10}$$

$$u_i = u_0\left[1-\sqrt{\sum_{i=1}^{Nt}\left(1-\frac{u}{u_0}\right)^2}\right] \tag{11}$$

Figure 2 shows a wind farm of having 7 wind turbines. The wind turbines T1, T2, T3 are facing free-stream velocity while the wind turbines T4, T5, T6 are operating in a single wake effect. The wind turbine T7 faces the wake effect from two upstream turbines T1 and T4. The calculation of wind speed deficit at the position of T7 has been done by using Equation no (11).

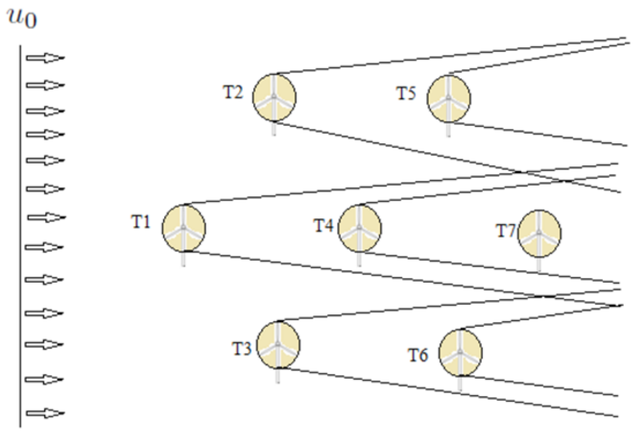

Figure 2. Multiple wake effect of wind farm.

2.3 Cost Model

The cost model used in present study gives non-dimensional cost of the wind farm as a function of the number of wind turbines[17,19]. The total cost is calculated using the following expression:

$$\text{Cost} = N_t\left[\frac{2}{3}+\frac{1}{3}e^{-0.00174N_t 2}\right] \tag{12}$$

Where N_t is the number of wind turbines purchased.

The objective function used to minimize the total cost per unit power of the wind farm and is given as follows:

$$objective = minimize\left(\frac{cost}{power}\right) \tag{13}$$

2.4 Efficiency Model

Efficiency is determined as a ratio between the amount of energy extracted from the wind farm and the total energy without wake. The numerator represents the actual energy extracted from the rotor of each wind turbine, considering the Betz limit of aerodynamic theory. The wind farm efficiency can be formulated using the equation depending on the number of wind turbines.

Total power produced in wind farm when considering wake effect can be calculated by using equation14:

$$power_{total} = \sum_{i=0}^{Nt}\left(0.3\times u_i^{\,3}\right) \tag{14}$$

Equation 15 is used to calculate the wind farm total power without wake effect:

$$power_{wf} = p * N_t = N_t\left(0.3\times u_o^{\,3}\right) \tag{15}$$

Where, p, is the rated capacity of each wind turbine.

The overall efficiency of the wind farm is calculated by using equation 16 and 17, as follows:

$$Efficiency = \frac{power_{total}}{power_{wf}} \tag{16}$$

$$Efficiency = \frac{\sum_{i=0}^{N_t}\left(0.3 * u_i^{\,3}\right)}{N_t\left(0.3 * u_o^{\,3}\right)} \tag{17}$$

The wind farm characteristics used in present research are given in Table 1. The characteristics of wind distribution can be described using Weibull probability distribution. In order to compare the obtained results the parameters of wind farm were similar as used in previous studies[16–19,24].

3. Optimization

In the wind farm layout optimization problem the basic and the most important thing is the land availability and its specific area dimensions. The wind farm layout optimization is a discrete problem and solving by using classical techniques makes it further complex and also requires using more variables.

3.1 Points of Zero Wake Effect

The overall power production of a wind farm can be increased by utilizing the whole available wind resource. This can be done by installing the maximum number of wind turbines at the all possible upstream positions. The zero wake effect points in the wind farm area can be calculated by using the following method.

Figure 3 shows the two wind turbines, WT_1 and WT_2 located within the wind farm with an arbitrary orange, O. and the given wind direction θ. The vector OWT1 represents the position of wind turbine WT1 and the position vector OWT2 represents the position of wind turbine WT2. Let point, B, is the first cone vertex of the WT1's wake in the direction of wind velocity. The angle, β, between the two vectors, originating from the cone vertex B of the wind turbine WT1 to the vector originating from B to the wind turbine WT2. The value of angle β is calculated as:

$$\beta = \cos^{-1}\left(\frac{\overrightarrow{(BWT1)}\overrightarrow{(BWT2)}}{L_{\overrightarrow{BWT1}}L_{\overrightarrow{BWT1}}}\right) \tag{18}$$

If the angle β between the the vectors BWT1 and BWT2 is grater than the angle, α, the wind turbine WT2 will be not lay in the wake effect of the wind turbine WT1 (21). For the multiple wake effect condition the angle β will be calculated by using the following equation.

$$\beta_{ij} = \cos^{-1}\left\{\frac{(x_i - x_j)\cos\theta + (y_i - y_j)\sin\theta + R/k}{\sqrt{\left(x_i - x_j + R/k\cos\theta\right)^2 + \left(y_i - y_j + R/k\sin\theta\right)^2}}\right\} \tag{19}$$

Table 1. Parameters and characteristics of wind farm

Hub height	60m
Rotor radius (r_d)	40 m
Thrust coefficient (C_T)	0.88
Swept area (m^2)	5080
Wind farm area (km^2)	$2km \times 2km$
Cell size (m^2)	200×200
Length of Surface roughness (m)	0.3
Free stream velocity (m/s)	12
Air density (kg/m^2)	1.2253

3.2 Parameters of Genetic Algorithm

Genetic Algorithm is based on the principles of chromosome genetic process. It comprises of randomly generated population (in this case, farm layouts). The steps in genetic algorithm involved for wind farm layout optimization are described below.

- The chromosome string constitutes a fixed wind farm area and a fixed number of wind turbines.
- Using the constraints given in Table 1, the defined number of chromosomes is generated. In this study, the number of chromosomes was set to 200, generating 200 (10 x 10) individuals. Each individual contained (N_t — 19) randomly placed wind turbines, where N_t is the total numbers of wind turbines.
- To place (N_t — 19) wind turbines in the aforementioned wind farm area, the objective function (cost per unit area) for each individual is calculated using Equation 13.

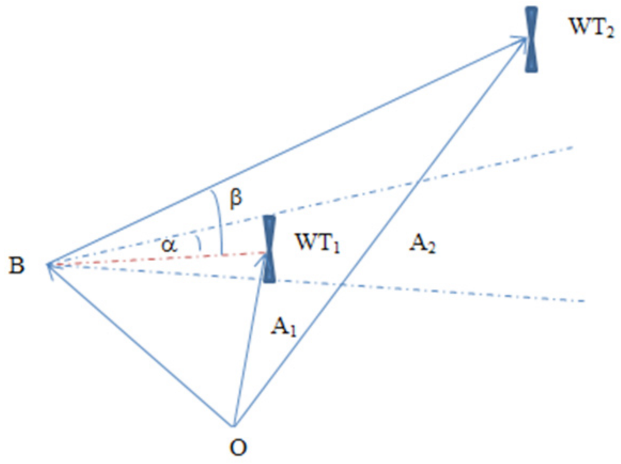

Figure 3. Wind turbine outside the wake effect of another wind turbine.

- At least 2 members of each individual need to be set to be reproduced in the next generation in this case.
- Crossover is the main step in GA. It is responsible for the execution of crossover of replicated chromosomes in the form of pairing. Crossover has many types. Two crossover methods utilized in this study were single-point crossover and two-point crossover, as shown in Figure 4 and 5, respectively.
- The fitness function is then computed for all individuals. Each generated fitness function will be compared with those of next generation. If the next generation fitness function is lower than the previous ones, they will be replaced by the last ones as new function. The previous fitness function is retained and this process is continued until the last generation.

Figure 6 presents the flowchart of the proposed process, where the objective is to find the least cost per unit area for the aforementioned wind farm dimensions.

Figure 7 shows the wind farm with proposed optimized layout of total 32 wind turbines. The first 19 wind turbines was placed at upstream wind positions and the genetic algorithm was used in the wind farm area left behind for the installation of remaining 13 wind turbines.

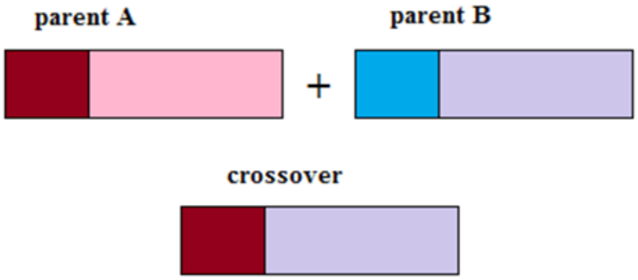

Figure 4. Single-point crossover.

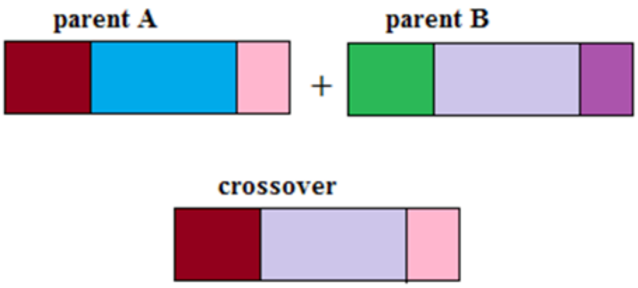

Figure 5. Two-point crossover.

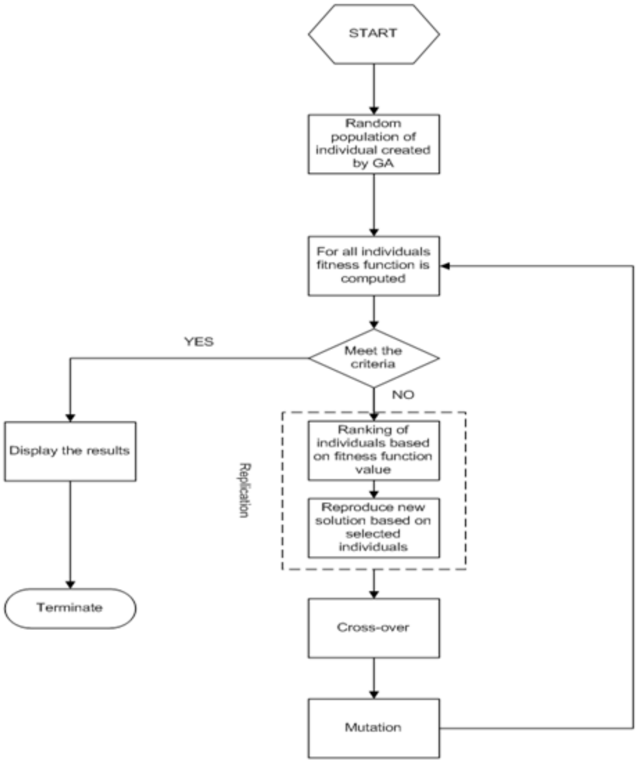

Figure 6. Flow chart of the process.

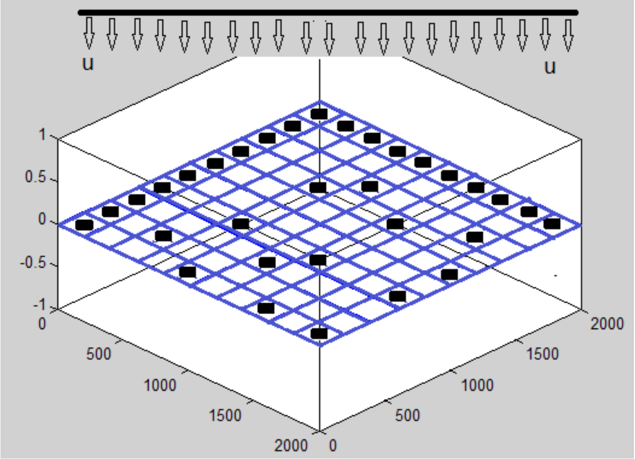

Figure 7. Proposed wind farm layout.

Table 2 enlists the power output of each turbine and shows the objective function values and the efficiency of wind farm, as well as addition of the wind turbines. It is observed that as we increase the number of wind turbines after 19th, the efficiency will decrease continuously.

The total efficiency of wind farm against the number of wind turbines is shown in Figure 8. The first 19 wind turbines faced the upstream wind velocity operated at their maximum efficiency (100%). After that, the wind farm efficiency decreases continuously with the placement of the wind turbines because of the wake effect losses.

Table 2. Power and efficiency calculation with number of wind turbines

No of wind turbine	Cost of turbine	Power (kW)	Cost per unit power	Efficiency (%)
1	0.99911	518.4	0.00197	100
2	1.99471	518.4	0.00194	100
3	2.98357	518.4	0.00191	100
4	3.96222	518.4	0.00191	100
5	4.92762	518.4	0.00190	100
6	5.87688	518.4	0.00189	100
7	6.80739	518.4	0.00187	100
8	7.71686	518.4	0.00186	100
9	8.60332	518.4	0.00184	100
10	9.46519	518.4	0.00182	100
11	10.3012	518.4	0.00180	100
12	11.1107	518.4	0.00178	100
13	11.8932	518.4	0.00176	100
14	12.6486	518.4	0.00174	100
15	13.3773	518.4	0.00172	100
16	14.0800	518.4	0.00169	100
17	14.7576	518.4	0.00167	100
18	15.4115	518.4	0.00165	100
19	16.0432	518.4	0.00162	100
20	16.6545	508.2344	0.00163	99.902
21	17.2471	505.5906	0.00162	99.789
22	17.8232	505.5906	0.00160	99.6862
23	18.3849	501.7759	0.00159	99.5604
24	18.9343	501.7759	0.00157	99.4451
25	19.4735	495.9931	0.00157	99.2944
26	20.0046	495.9931	0.00155	99.1553
27	20.5297	486.6481	0.00156	98.9598
28	21.0507	486.6481	0.00154	98.7782
29	21.5695	486.6481	0.00158	98.4998
30	22.0877	486.6481	0.00156	98.2399
31	22.6068	470.2074	0.00155	97.9971
32	23.12825	470.2074	0.001537	97.769

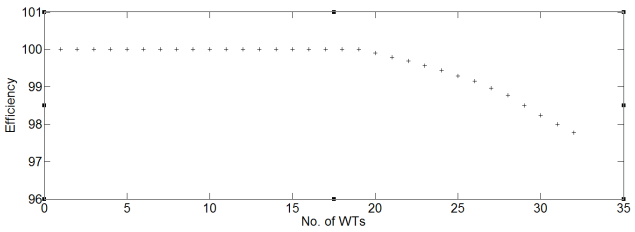

Figure 8. Graph of efficiency against number of turbines.

4. Results and Discussion

In this section, the obtained results from present research for constant wind speed 12m/s with uniform direction are presented and compared to the results from earlier studies[16–18, 20, 22, 25, 28]. In present study, we considered a wind farm of total area $2km \times 2km$, similar as in all previous studies, except Mittal's work who used grid of dimensions of $2km \times 2.2km$. The wind farm area is divided into 100 squares with each having dimensions of $5D \times 5D$, where D is the diameter of wind turbine rotor. A wind turbine can be placed at the center of each square, so that the distance between the two adjacent turbines will not exceed 200 m.

Figure 9 shows the proposed wind farm layout and the optimal layouts proposed by[16–18, 20, 22, 25, 28]. The authors of [22,25,28] are proposed the same layout as given by Grady et al.[17]. The black boxes indicate the positions of wind turbines.

The optimal layout described by Mosetti et al.[16] was not balanced, as shown in Figure 9. This was because the wind was unidirectional and had a fixed speed. Therefore, for all columns, the wind conditions were identical. They utilized the first three rows for the placement of the first 9 wind turbines, which showed that they could not utilize the space correctly. By using 26 wind turbines, Mosetti obtained a total power of 12,352 kW with objective function value of 0.001197, while the proposed layout is able to extract 13,364.55 kW with fitness function value of 0.001551 by using the same number of turbines. The efficiency difference between the results from the present study and Mosetti results is listed in Table 3.

The values described by[17,22,25,28] were proportional because they optimized a single column and interpreted the outcomes to all the other columns. The symmetrical configuration had an objective function value lower

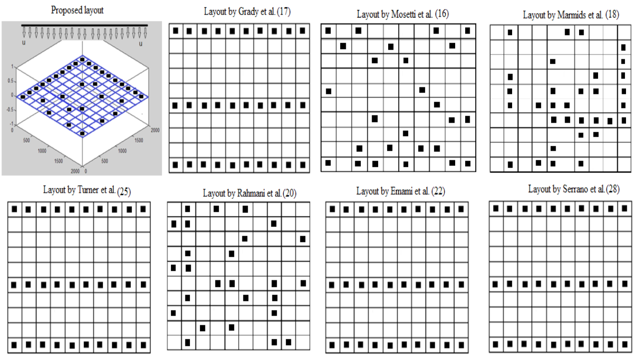

Figure 9. Proposed optimal layouts by earlier studies[16–18,20,22,25,28] and present work.

than that obtained by Mosetti et al.[16]. Table 4 lists the comparison between results obtained by[17,22,25,28] and present study. They used a total of 30 wind turbines in the wind farm, and obtained a total power of 14,310 kW with objective function value of 0.0015436 and efficiency of 92.015%. In comparison, present wind farm layout with 30 turbines gave a total power of 15,311.15 kW with objective function value of 0.001513 and the efficiency of the wind farm 98.2398%.

Table 5 shows the optimization comparison between the results from the present research and Mittal[19] by using 32 number of wind turbines. Mittal‘s optimized layout gave a total power of 15,218.2 kW with efficiency of 91.74% and 0.00155 objective function value. The present study shows that by using 32 wind turbines, the 16,251.56 kW power can be obtained with efficiency of 97.7688 % and an objective function value of 0.001537.

Table 3. Efficiency difference between the present study and Mosetti et al.[16]

	Mosetti et al.	Present results
No. of wind turbines	26	26
Total power (kW)	12352	13,364.55
Objective function	0.0016197	0.001551
Efficiency (%)	91.645	99.15534

Table 4. Efficiency difference between the present study and[17,22,25,28]

	Reference (17, 22, 25, 28)	Present study
No. of wind turbines	30	30
Total power (kW)	14,310	15,311.15
Objective function	0.0015436	0.001513
Efficiency (%)	92.015	98.2398702

Table 5. Efficiency difference between the present study and Mittal[19]

	Mittal	Present study
No. of wind turbines	32	32
Total power (kW)	15,218.2	16,251.56
Objective function	0.00155	0.001537
Efficiency (%)	91.74	97.7688

Table 6. Efficiency difference between the present study and Rahmani et al.[20]

	Rahmani et al.[20]	Present study
No. of wind turbines	26	26
Total power (kW)	12,819	13,364.55
Objective function	0.01539	0.1551
Efficiency (%)	95.11	98.2398

The optimal layout of wind farm proposed by Rahmani et al.[20] shows that they did not use wind turbine in Column 1 and 3, which is disputable, because these columns were not employed as the direction of wind was along the column. Moreover, the tenth and sixth columns were filled by placing the turbines back to back, which might have distressed the power and efficiency from these turbines because of great wake effect. By using 26 wind turbines, they obtained 12,819 kW of power with objective function value 0.01539 and the efficiency 95.11 %. Meanwhile, the proposed wind farm layout is obtained 13,364.55 kW power with objective function value of 0.1551 and 98.2398 % efficiency with the same number of wind turbines.

5. Conclusion

Wind farm layout optimization is important for harnessing maximum wind energy. The present study proposed the modeling of wind farm layout optimization for the reduction of wake effect losses to obtain optimized layout for onshore as well as offshore wind farms. The developed genetic algorithm programming formulations for the wind turbine positioning problem was presented that considered all interactions between turbines. The presented layout shows effectiveness of the dimension of the area used for a wind farm. The fixed placement of the wind turbines is assumed to be beneficial for the use of upstream wind. With the help of two level optimization framework the obtained results noticeably improved as compared to the mostly previous research in terms of overall wind farm efficiency. The proposed wind farm layout requires placement of 19 turbines where no wake effect should affect the power output, whereas the remaining 13 turbines are placed using GA algorithm. The efficiency of the proposed wind farm was found to be 97.7 % and total power available was 16,251.56 *kW* for the placement of 32 wind turbines. The objective function (cost per unit power) was calculated to be 0.001537.

6. References

1. Raheem A, Hassan M Y, Shakoor R. Pecuniary optimization of biomass/wind hybrid renewable system. Proceedings of the 1st International Conference on Energies, Sciforum

Electronic Conference Series c006; 2014 Mar 14–31. p. 1-10.

2. Fried L, Shukla S, Sawyer S. Global Wind Report: Annual market update 2011. GWEC; 2012. Available form: http://www.gwec net/publications/globalwind-report-2
3. Energy Agency I. International Energy Agency WIND 2012 Annual Report [Online]. 2012.
4. Moskalenko N, Rudion K. Study of wake effects for offshore wind farm planning. 2010.
5. Vermeer LJ, Sorensen JN, Crespo A. Wind turbine wake aerodynamics. Progress in Aerospace Sciences. 2003; 39 (6–7):467–510.
6. Jensen NO. A Note on Wind Generator Interaction. 1983. Technical Report: Riso-M-2411.
7. Ishihara T, Yamaguchi A, Fujino Y. Development of a new wake model based on a wind tunnel experiment. Global Wind Power. 2004.
8. Frandsen S, Barthelmie R, Pryor S, Rathmann O, Larsen S. Deficit in large offshore wind farms. 2006 Jan; p. 39–53.
9. Werle M. A new analytical model for wind turbine wakes. 2008. Report No: FD.200801.
10. Schepers J, Van der Pijl S, editors. Improved modelling of wake aerodynamics and assessment of new farm control strategies. Journal of Physics: Conference Series; IOP Publishing; 2007.
11. Crasto G, Gravdahl AR, editors. CFD wake modeling using a porous disc. European Wind Energy Conference & Exhibition; 2008.
12. Wu Y-K, Lee C-Y, Chen C-R, Hsu K-W, Tseng H-T. Optimization of the Wind Turbine Layout and Transmission System Planning for a Large-Scale Offshore Wind Farm by AI Technology. IEEE Transactions on Industry Applications. 2014; 50(3):2071–80.
13. Migoya E, Crespo A, Garcia J, Moreno F, Manuel F, Jimenez A, et al. Comparative study of the behavior of wind-turbines in a wind farm. Energy. 2007; 32(10):1871–85.
14. Aytun Ozturk U, Norman BA. Heuristic methods for wind energy conversion system positioning. Electric Power Systems Research. 2004; 70(3):179–85.
15. Sanderse B. Review of computational fluid dynamics for wind turbine wake aerodynamics. Wind Energy. 2011 Feb; p. 799–819.
16. Mosetti G, Poloni C, Diviacco B. Optimization of wind turbine positioning in large windfarms by means of a genetic algorithm. Journal of Wind Engineering and Industrial Aerodynamics. 1994; 51(1):105–16.
17. Grady SA, Hussaini MY, Abdullah MM. Placement of wind turbines using genetic algorithms. Renewable Energy. 2005; 30(2):259–70.
18. Marmidis G, Lazarou S, Pyrgioti E. Optimal placement of wind turbines in a wind park using Monte Carlo simulation. Renewable Energy. 2008; 33(7):1455–60.
19. Mittal A. Optimization of the layout of large wind farms using genetic algorithm [MS thesis]. Department of Mechanical and Aerospace Engineering, Case Western Reserve University; 2010.
20. Rahmani R, Khairuddin A, Cherati SM, Mahmoud Pesaran HA. A novel method for optimal placing wind turbines in a wind farm using Particle Awarm Optimization (PSO). 2010 Conference Proceedings IPEC; 2010. p. 134–9.
21. Kusiak A, Song Z. Design of wind farm layout for maximum wind energy capture. Renewable Energy. 2010; 35(3):685–94.
22. Emami A, Noghreh P. New approach on optimization in placement of wind turbines within wind farm by genetic algorithms. Renewable Energy. 2010; 35(7):1559–64.
23. Rajper S, Amin IJ. Optimization of wind turbine micrositing: A comparative study. Renewable and Sustainable Energy Reviews. 2012; 16(8):5485–92.
24. Chen Y, Li H, Jin K, Song Q. Wind farm layout optimization using genetic algorithm with different hub height wind turbines. Energy Conversion and Management. 2013; 70:56–65.
25. Turner SDO, Romero DA, Zhang PY, Amon CH, Chan TCY. A new mathematical programming approach to optimize wind farm layouts. Renewable Energy. 2014; 63:674–80.
26. Shakoor R, Hassan M Y, Raheem A, Rasheed N, Mohd Nasir MN, editors. Wind farm layout optimization by using definite point selection and genetic algorithm. 2014 IEEE International Conference on Power and Energy (PECon 2014); 2014; IEEE Digital Explore.
27. Goldberg DE, Holland JH. Genetic algorithms and machine learning. Machine learning. 1988; 3(2):95–9.
28. Gonzalez JS, Gonzalez Rodriguez AG, Mora JC, Santos JR, Payan MB. Optimization of wind farm turbines layout using an evolutive algorithm. Renewable Energy. 2010; 35(8):1671–81.