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# OPTIMAL WIND TURBINES POSITIONING IN A WIND FARM: A CASE STUDY OF THE MIL NADER REGION

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**Abstract-** This paper represents a method to determine the optimal location of wind turbines in a wind farm. Some important factors should be considered when wind turbines are placed within a wind farm to achieve the highest efficiency. In this study, the position of turbines are determined to extract the maximum annual energy by reducing the wake effect in the farm. In addition, the road construction and cabling costs have been also considered as the objectives of the problem. To implement this optimization method, we have used an annual wind data including wind speed and direction, measured with ten-minute intervals for Mil Nader region in Iran. This region has high potential for installing a wind farm due to the high wind speed during a year. Genetic algorithm is applied for optimization of this multi-objective problem. The simulation results of the proposed method, compared to some other sitting methods, demonstrate that the proposed method is capable of reducing the investment costs for installation of a wind farm and it can increase the annual output energy by reducing the wake effect.

**Keywords:** Wind Farm, Wake Effect, Road Cost, Cabling Cost, Genetic Algorithm.

## I. INTRODUCTION

Wind energy is one of the clean and sustainable energies in the world. This penetration of this energy is increasing in power system; as a result, different studies have been devoted to this field. In [1], modeling of power producing characteristics for some specified regions of the Caspian Sea is carried out on the basis of long term observations and measurement of average wind speed and gusts as well as sea excitement. Increasing the number of wind farms in the power system has caused this factor is considered in the power system planning studies [2]. Wind farm design and investment in this field is very important from techno-economic standpoint. Turbines in a wind farm can be located with a specified arrangement. Wind turbines installation and operation have some variable and constant costs. A part of wind turbine installation cost is constant whether one turbine is considered or more.

Therefore, this cost can be divided among some turbines in a wind farm and as a result, the total cost decreases. If wind turbines are installed in different locations, each of them requires separate equipment to be connected to the grid whereas, the turbines installed in one area can be connected to the grid with collective equipment. However, there are some problems in the wind farms such as efficiency reduction due to the wake effect, maintenance cost increment because of oscillation intensification, etc. [3]. Installing wind turbines in a wind farm is easier, more economic and efficient, comparing to separate installation of wind turbines. To design a wind farm, some important factors should be considered such as maximum capacity, location, noise, wake effect and total costs [3-5].

In [4, 5], a method has been proposed to design a wind farm to achieve the maximum profit. In [6] Monte Carlo algorithm has been used to optimally find the place of wind turbines in a wind farm. A new method for sitting of wind turbines using Particle Swarm Optimization (PSO) algorithm has been implemented in [7]. In [8], different wake effect models, with details for various wind farms in china, have been studied. In [9], a compact model of several wind turbines has been presented. Different compact models for using in simulation of power system dynamic have been stated in [10].

In [11], a model for describing the wake effect as a result of partial overlapping of the shaded areas of the rotating plane of upstream and downstream wind turbines has been represented. Due to the importance of wind farm design, sizing, and placement, many research works has been implemented in this field and some of them was mentioned. Therefore, to address this problem for a real case study, we have implemented a method to optimally find the best positions of wind turbines located in a wind farm.

This study represents a wind turbine sitting method in a wind farm for Mil Nader region in Iran. The objective function of this study is to maximize the output power of wind farm, minimize the wake effect, and total costs related to road construction and cabling within the wind farm.

In section II, a nonlinear model is described to model the wake effect in the wind farm. A mathematical model is represented to model the road construction costs among turbines of the wind farm in section III. Section IV is devoted to the design of the collector in four steps, considering the minimum cabling. The Objective function of the problem is discussed in section V, followed by giving the data of the utilized turbines and simulation results in section VI and VII, respectively. Finally, the conclusions are given in section VIII.

## II. WAKE EFFECT MODELLING

The air mass, which leaves a turbine, has lower energy content because of the effects of wind turbine on the wind speed. This shadowing effect of the upstream turbines on the downstream turbines is known as wake effect. This effect is related to the geometry of blades and it can decrease the efficiency of the downstream turbines, if a proper distance among turbines is not considered. The output power of a wind turbine is a function of wind speed. Therefore, anything that decreases the wind speed can reduce the efficiency of a wind turbine. Wake effect can be decreased by increasing the distance between turbines.

Wake effect can be simulated in two steps. In the first step, wind turbines positions are determined. In addition, the wake effect of all turbines on each turbine should be considered. In the second step, the wake effect of each turbine on the wind speed should be calculated.

After determination of wind direction in the specified time, for each turbine, it should be determined which turbine has wake effect on the selected turbine. Therefore, the relative position of each turbine to the others should be determined using a simple method. It is possible to determine the position of the majority of the turbines to the selected turbine with a little calculation efforts. In so doing, according to the wind direction, it should be determined, for each turbine, whether it is affected by upstream turbines or downstream turbines. By Appling this simple way, the calculations are considerably decreased.

Each turbine is specified by its coordinates ($X_n$, $Y_n$). $\theta$ expresses the wind direction toward the turbine and $\theta = 0$ is the north direction so according to Figure 1, if $90 < \theta < 270$ the wind turbine of ($X_n$, $Y_n$) coordinates, is affected by downstream wind turbines wake effects ($Y_i$<$Y_n$) and if $0 < \theta < 90$ or $270 < \theta < 360$ the turbine is influenced by upstream wind turbines wake effects ($Y_i$>$Y_n$). This simple way helps to omit many states rapidly and for the other turbines the accurate model should be used which is explained in following.

Generally, three models including Jensen Model [12], Ainslie model [13] and G.C. Larsen model [14] can be used to model the wake effect in a wind farm. In this study, Jensen model is used to calculate the wind speed in the downstream turbines. This model is a simple analytical model, which was represented by N.O. Jensen in 1983. Figure 2 shows Jensen basic model in which cylindrical coordinates system has been used.

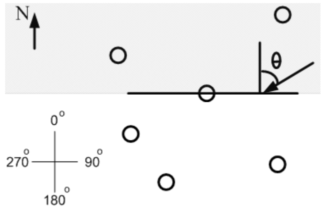


Figure 1. Consideration of the wake effect

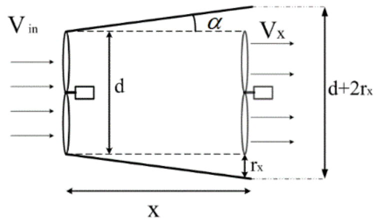


Figure 2. General form of Jensen model

Wind speed for downstream wind turbines is calculated by using equation 1 as following [4]:

$$V_x = V_{in}\left[1-(1-\sum_{i}^{n}\sqrt{1-C_t})(\frac{d}{d_{xi}})^2\right]\frac{\ln(h/h_0)}{\ln(h_{ref}/h_0)} \quad (1)$$

where, $V_{in}$ is free wind speed or the wind speed in upstream wind turbine, $V_x$ is the wind speed in downstream wind turbine, $h_{ref}$ is the hub height and $h_0$ is roughness length and varies according to the geographical location, $C_t$ is thrust coefficient which can be obtained from wind turbine catalogue, $d$ is the diameter of the upstream turbine rotating plane and $d_x$ is the diameter of downstream turbine which is calculated as follows:

$$d_x = d + 2r_x = d + 2kx \quad (2)$$

where, $r_x$ , $k$ and $x$ are shown in Figure 2. The $k$ is a coefficient which determines the amount of wake effect on the wind speed decrement. The value of $k$ for onshore and offshore wind turbines is around 0.075 and 0.05, respectively. In this study, the value of $k$ is 0.075. The value of angle $\alpha$ can be calculated by equation (3) and usually is equal to 0.08 [15].

$$\alpha = \frac{1}{2\ln(\frac{h_{ref}}{h_0})} \quad (3)$$

According to this model, wake effect for each turbine is determined considering the angle $\alpha$ and the distance from the selected turbine. It is illustrated in Figure 3, to determine which turbines affect the selected turbine, a line proportional to the wind turbine rotor diameter is considered. This line, which is perpendicular to the wind direction, is specified as line AB in Figure 3. Then, the equations of line AC and line BD are obtained from the information of point A and B and angles $\theta-\alpha$ and $\theta+\alpha$.

Now, the selected turbine is under the influence of the wake effect of all turbines, located in the trapezoid ABCD. These calculations are done for all turbines to determine the position of all turbines to each other and finally according to the distance from the selected turbine, rotor diameter and coefficient $k$, the influence of each turbine on the wind speed decrement is calculated by Equation (1). If several turbines are located in the same direction, the wind speed from upstream turbine to the downstream turbine is calculated by the stated method step by step.

As can be seen in Figure 3, when wind passes from the first turbine, located in distance $D_1$ from the second turbine, its speed decreases from $V_1$ to $V_2$. For the third turbine, the wind speed decrement is related to the distance $D_2$.

$$V_1 \xrightarrow{D_1} V_2 \xrightarrow{D_2} V_3;\ \ V_1 \rangle V_2 \rangle V_3 \qquad (4)$$

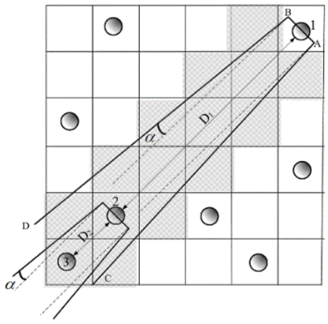

Figure 3. Wake effect modeling

## III. MATHEMATICAL MODEL FOR OPTIMIZATION OF ROADS IN THE WIND FARM

To construct the roads in a wind farm, the distance of each turbine to the other turbines and to the main roads should be obtained. Then, for each turbine, the shortest path is selected. Finally, a wind farm is divided to several groups. The turbines of each group are connected to each other but some of these groups may be disconnected from the main roads. Therefore, all groups should be evaluated to be sure that one turbine in each group is connected to the main road. If a group is disconnected from the main roads, it should be connected by the closest turbine to the main roads or another group, which is connected to the main road. In fact, to minimize the road costs in a wind farm, the following function should be considered.

$$\text{minimize} \sum_{j=1}^{n_g} \sum_{i=1}^{n_t} X_i \qquad (5)$$

where, $n_t$ is the number of turbines in each group, and $n_g$ is the number of turbine groups. For example, if there are five turbines in a group, at least five roads is required to connect turbines to each other and to main road or to other group and this process for all groups should be done.

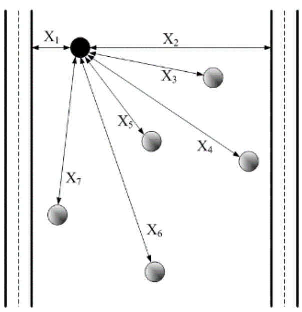

Figure 4. Calculation of the minimum roads in the wind farm

Figure 4 shows an assumed wind farm with two main roads. In Figure 4 for specified turbines, the distances from the main roads are calculated and a turbine with the minimum distance is selected for connection to main road.

## IV. MATHEMATICAL MODEL TO OPTIMIZE CABLES RELATED TO COLLECTOR DESIGN

The designing of the collector includes 4 stages which are described in the following section.

### A. Turbines Classification

If the number of turbines, which should be connected to the substation is large, the required cable should have a high capacity. Therefore, by increasing the number of turbines, selection of an appropriate cable is impossible or this cable will be very expensive. To avoid this problem, wind turbines should be classified in several groups and each group should be connected to the substation separately. To classify wind turbines, a number of lines are drawn from substation in the first step. Each line is equivalent to one group; the number of the lines and the distance between them are determined based on the following parameters:

- Substation location.
- Total number of wind turbines.
- The number of turbines in the same group according to the used cables.

To determine the number of lines, the number of turbines at each group is specified by the cable capacity. Then, the total number of turbines is divided by the number of turbines in each group. The result represents the number of groups or lines in the wind farm. To determine the angle or the distance among the lines, 360 degrees should be divided by the number of lines. The obtained result is the angle among the lines. In the second step, the distance of each turbine from all lines is calculated and each turbine is connected to the closest line. For example, Figure 5 shows a wind farm with 55 turbines. The number of turbines in each group is 10. Therefore, the number of lines or groups is 6 and the angle among these lines is 60 degrees.

55/10 = 5.5

Number of groups = 6

360º / 6 = 60º

The following equation can be used to determine the number of groups and the angle between the lines drawn from substation to classify the turbines.

$$N_g = \frac{N_t}{N_{tg}} \qquad (6)$$

$$\beta = \frac{360}{N_l} \qquad (7)$$

where, $N_g$ is the number of groups in the wind farm, $N_t$ is the number of turbines in the farm, and $N_{tg}$ is the number of turbines in each group, $\beta$ is the angle between lines and $N_l$ which is equal to $N_g$ is the number of lines drawn from substation.

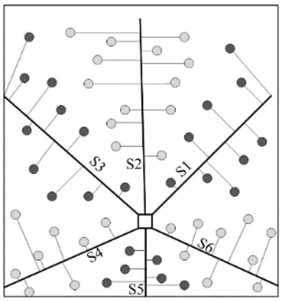


Figure 5. Wind turbines classification

In the next step, all lines are checked and if the number of connected turbines to each line is greater than a specific number, a new line is added between this line and one of its surrounding lines, since the area between them is more congested and this process is repeated from step two to the end. As can be seen in Figure 5, the number of connected turbines to one of the lines is more than the limits so the corrected classification with a new line is shown in Figure 6. For minimization of cabling among turbines, spanning tree should be drawn for each group. The algorithm of aforementioned steps is shown in Figure 7.

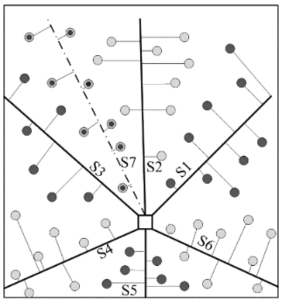


Figure 6. The corrected form of Figure 5

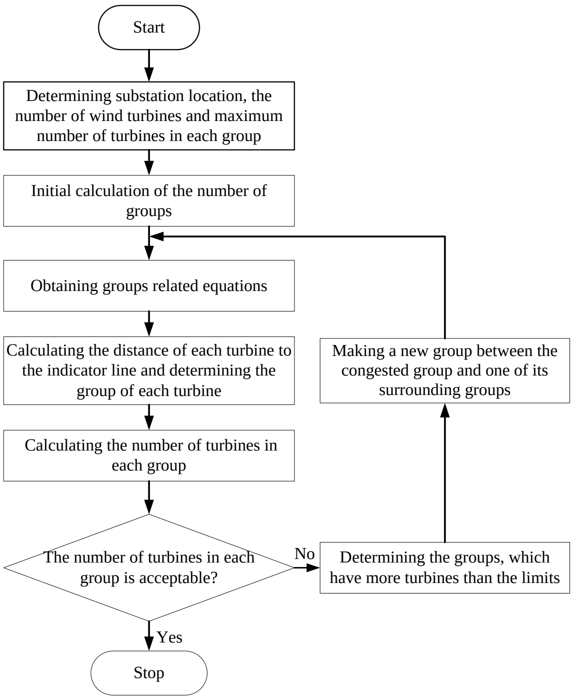


Figure 7. The flowchart of wind turbines classification

## B. Minimum Spanning Tree

To minimize cabling in the wind farm, any two turbines should be connected by exactly one cable. This concept is similar to the definition of a tree in graph theory. Therefore, graph theory is used for optimization in which vertices of the graph are turbines, branches of the graph are cables, and cabling among the turbines is equivalent to a tree.

In a graph, the tree which passes from all vertices is called spanning tree. If weighting coefficients are considered for the branches of a graph, the minimum spanning tree is a tree in which the summation of weighting coefficients of branches is the least among all spanning trees.

This concept can be used to design a collector in which weighting coefficients are the cost of cables. If the distance between two turbines is increased, the cabling becomes more expensive.

In this paper, Kruskal algorithm is used to find the minimum spanning tree [16]. The steps of this algorithm are given as follows:

1. Omitting all branches of a graph until just vertices remain.
2. Arranging all branches of the graph according to the weighting coefficients (cost of cables).
3. Adding branches to the graph from branches which have the least weighting coefficient. In this process, if adding a new branch creates a loop in a graph, that branch is ignored and the next branch is added to graph.
4. If the graph has $N$ nodes, the minimum spanning tree is obtained by adding $N$-1 edges.

The algorithm of the above stages is shown in Figure 8.

Using the above algorithm, minimum spanning tree that means cabling with minimum cost is obtained.

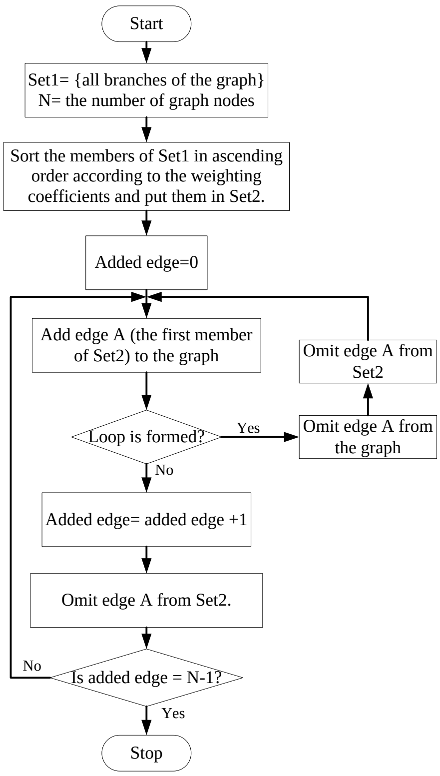


Figure 8. The flowchart of Kruskal algorithm

### C. Selection of Cable Type for Each Branch

As mentioned in the previous sections, turbines in a wind farm are classified in several groups and each group is electrically connected to the substation, independently. Three types of cable are considered in this study, which have different costs and capacities. These types are named A, B and C and their capacities are increased from A to C, respectively. Turbines in each group have a radial structure, which is similar to the distribution system structure. Therefore, by applying a power flow on each group, the current of each cable is obtained. At first, all cables are chosen from type A, which is the cheapest cable. After applying power flow and obtaining the currents of the branches, the overloaded branches are replaced by type B cables. Then, power flow is applied again and the overloaded branches are replaced by type C cables. If type C cable, which has the highest capacity, cannot solve the overload problem in some branches, two cables should be used in parallel. The process of the cable selection continues until no overloaded branches remain. The information of the three types of used cables in this study is given in Table 1[17]. The maximum ambient earth temperature is 25 degree C.

Table 1. The types of utilized cables

| Nominal area of conductor mm$^2$ | Current ratings (Amp) | AC resistance at 25 Deg C (Ohm/Km) |
|---|---|---|
| 50 | 204 | 0.494 |
| 120 | 351 | 0.196 |
| 300 | 606 | 0.079 |

### D. Calculation of Midpoints

To connect all turbines of each group to the grid, each turbine is connected to another turbine by shortest path or it can be connected to a point between two other turbines. Sometimes connecting a turbine to midpoints needs a shorter cable than connecting it to another turbine. To find midpoints, the closest turbine to the substation is directly connected to the substation in each group and for the other turbines, BFS (Breadth First Search) algorithm which is one of the graph traversal algorithm is used. Figure 9 shows this process and the steps of this process is explained in the following.

For each vertex or node like node b, a branch between this node and another node which is closer to the base node or substation is considered (branch ab in Figure 9) and two nodes of this branch are saved in $set_1$.

$$set_1 = \{a, b\} \tag{8}$$

In the next step, all nodes which have been connected to the point *b* except node *a*, are found and are saved in $set_2$.

$$set_2 = \{c, d\} \tag{9}$$

Now, from each node in set 2, a perpendicular line is drawn to the line ab. If *x* and *y* of intersection point are in the range of *x* and *y* of the members of set 1, this point is considered as a midpoint. Otherwise, midpoint is not existed and a branch, which has been obtained from minimum spanning tree, is the shortest path. As can be seen in Figure 9, for node d midpoint is existed but there is not any midpoint for node *c*. This procedure is performed for all nodes of a graph. The aforementioned stages are shown in Figure 10.

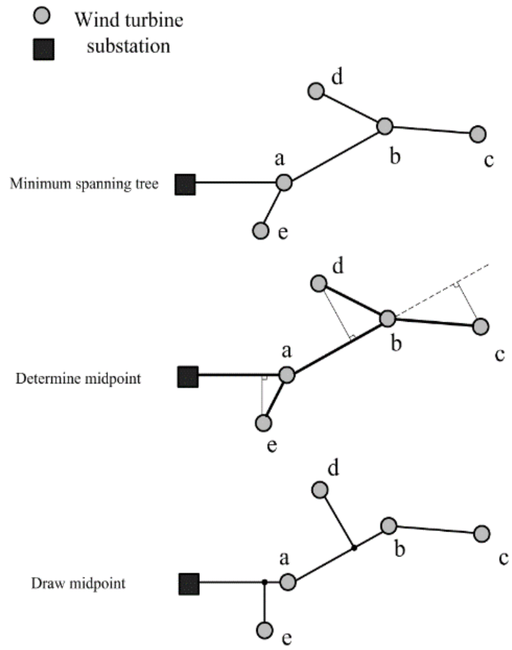


Figure 9. The midpoint search

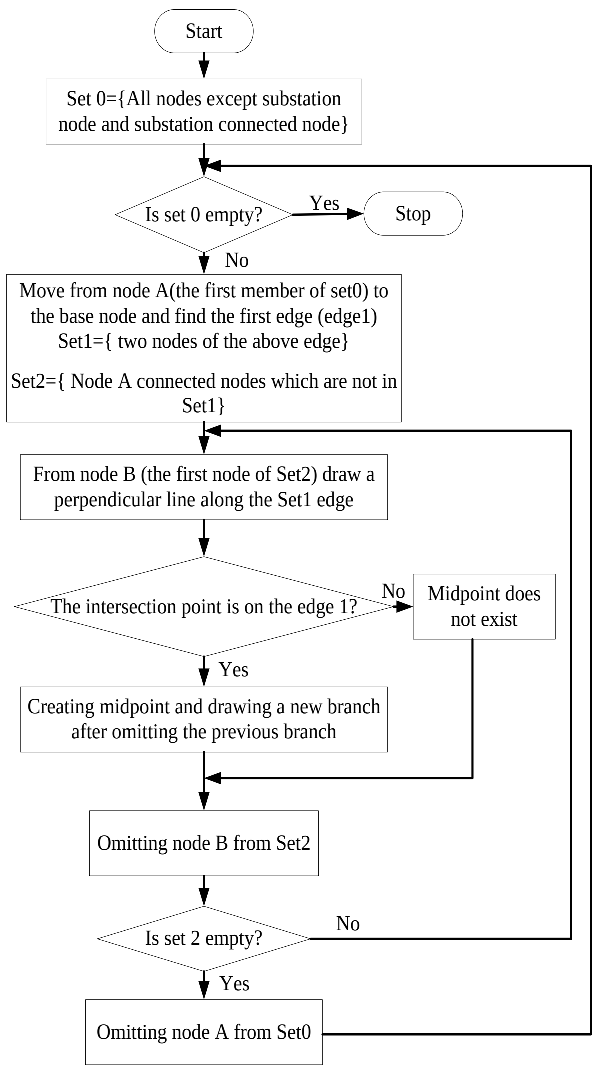


Figure 10. The flowchart of the midpoint search

## V. OBJECTIVE FUNCTION

The objective functions of this study is to minimize the annual cost of energy (COE) by reducing the investment cost and maximizing the extracted power by reducing the wake effects. A wind farm investment costs mainly include WTs cost, Cabling and road construction cost. The aforementioned costs can be calculated as follows:

The WTs related cost in a wind farm is calculated by Equation (10):

$$Cost_t = N_t[2/3 + 1/3e^{-0.0074N_t^2}] \quad (10)$$

where, $N_t$ is the number of wind turbines in a wind farm which is a variable number and $Cost_t$ is the WTs related cost in a wind farm. Equation (11) gives the cabling investment cost:

$$Cost_c = \sum_{j=1}^{N_l} L_j C_C + C_{Co} \quad (11)$$

where, $Cost_c$ is the cabling cost, $L_j$ is the length of $j$th line, which connects the $j$th turbine to the substation, and $C_C$ is the cabling cost per Km, and $C_{Co}$ is the collector cost. The road construction cost can be obtained using Equation (12):

$$Cost_c = \sum_{j=1}^{N_l} L_j C_C + C_{Co} \quad (12)$$

where, $Cost_r$ is the road construction cost, $L_i$ is the $i$th path length, $C_r$ is the cost of constructed road per Km. $N_r$ is the total number of paths in the wind farm, and $C_{fix}$ is the cost of main roads construction. Therefore, the total cost is as follows:

$$Cost_{Total} = Cost_t + Cost_c + Cost_r \quad (13)$$

On the other hand, the turbines should be placed in a way to have the maximum annual energy by reducing the wake effect. Hence, another term in objective function is maximizing the annual energy. Therefore, the final objective function is as follows:

$$F = \min(w_1 \times Cost_{Total} + w_2 \times \frac{1}{E_{annual}}) \quad (14)$$

where, $E_{annual}$ is the annual output energy of the wind farm, $w_1$ and $w_2$ are the weighting coefficients.

## VI. THE UTILIZED WIND TURBINES AND THE TOPOLOGY OF AN EREA

In some areas, there are several prohibited zones such as protected area for animal, lakes, swamp, etc. If a selected area for installing a wind farm includes prohibited zones, no turbine should be installed in these areas. In simulation, it is possible to prevent this problem by considering a penalty factor for prohibited zones. The case study of this research, however, does not include prohibited zones. The utilized wind turbine is XE93-2000 model and its parameters are given in Table 2.

Figure 11 shows $C_t$ curve versus wind speed. $C_t$ depends on the different factors such as air density and rotor radius. In Figure 12, the wind turbine output power versus the wind speed has been depicted. $C_t$ curve and power curve can be divided to four regions considering the wind speed.

In the first region, wind turbine cannot generate power because of low wind speed. In the second region, where the wind speed is between the cut-in and the rated wind speeds, the output power of wind turbine increases as wind speed rises and $C_t$ remains constant. In the third region, where the wind speed is above the rated wind speed and below the cut-out wind speed, as wind speed increases $C_t$ decreases to limit the output power to the rated power. Finally, in the region 4, where the wind speed is above the cut-out wind speed, the wind turbine is shut downed and disconnected from the grid.

Table 2. Some parameters of the wind turbines

| | | |
|---|---|---|
| Rated Wind Speed | m/s | 11 |
| Cut-out Wind Speed | m/s | 22 |
| Cut-in Wind Speed | m/s | 3 |
| Blade Length | m | 45 |
| Rated Power | kW | 2156 |
| Rated Voltage | V | 690 |
| Hub Height | m | 80 |
| Rotor Diameter | m | 93.4 |
| Rated Line Voltage | V | 660 |

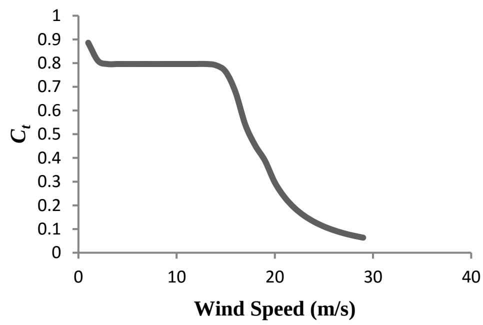


Figure 11. The $C_t$ curve versus wind speed

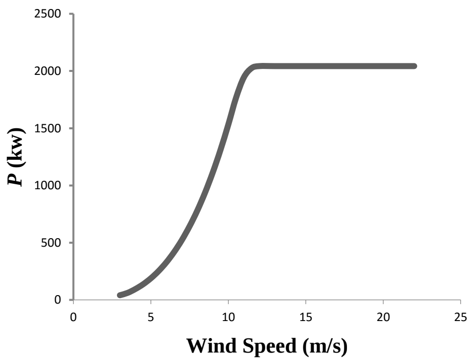


Figure 12. Wind turbine output power versus wind speed

## VII. SIMULATION RESULTS

In this study, annual wind data for Mil Nader region including wind speed and direction, measured with ten-minute intervals, have been used in simulations.

The wind rose for different wind directions has been depicted in Figure 13. It is obvious from Figure 13, the dominant wind direction is between 30 and 60 degree of geographic north.

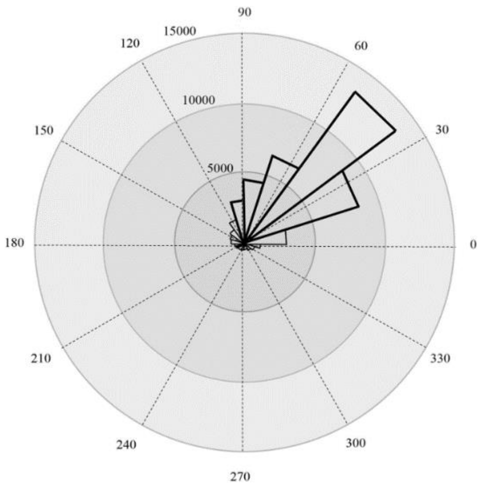


Figure 13. Wind rose for different wind directions of the selected region

Genetic algorithm has been used in this study to solve this optimization problem. To implement the algorithm, a square area, with 4 km length of each side, has been divided to 400 equal parts. Therefore, 400 squares with 200 meters side length are available. Each square is known as a cell and just one turbine can be installed in each cell. Therefore, the length of each chromosome in genetic algorithm is 400. Each turbine has two states, 1 and 0; if a turbine is installed in a cell, the state of the cell is 1 otherwise the state of the cell is 0.

In the first step, genetic algorithm generates a random population. The initial population size has been considered as 100. In the next step, the fitness function for each member of the population or possible solutions are calculated and the solutions with higher fitness are selected and considered as parents for the next generation. In the next step by applying crossover and mutation operators on the selected individuals, the next generation population is generated.

For the new population, fitness function is calculated and the individuals with higher fitness are selected. This procedure continues until one of the following conditions is satisfied.

- The solution which satisfies the stopping condition is obtained.
- When the user-specified maximum number of iterations is run.

Crossover and mutation rate are considered 0.8 and 0.05, respectively. At each stage of algorithm, after determining the value of each gene, turbines locations and their positions to each other are determined. In addition, the road length, cable capacity, and wake effect of turbines on each other are evaluated, finally, fitness function is calculated and the optimal solution is obtained.

Simulation results of wind turbine sitting for Mil Nader region, considering different wind speeds and directions, have been shown in Figure 14. Two main roads are available for this farm. Figure 15 shows the optimal roads among turbines.

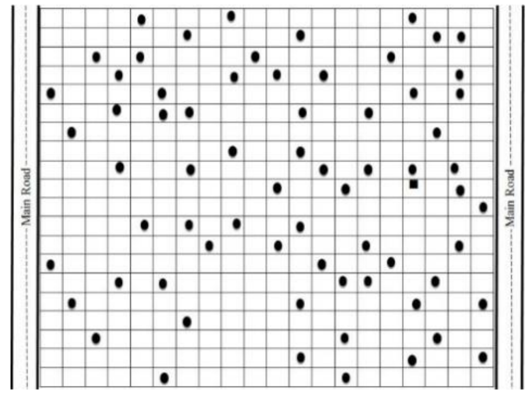


Figure 14. The optimum turbines sitting in the wind farm

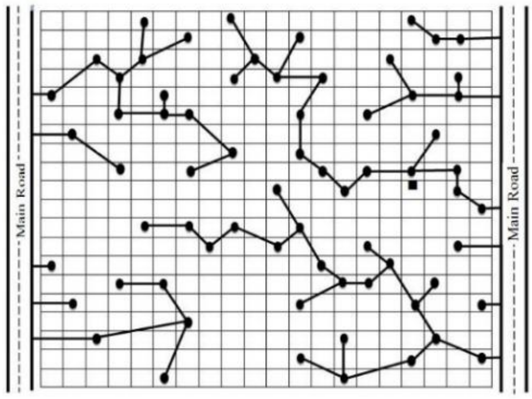


Figure 15. How constructing the optimum roads among turbines

Figure 16 illustrates the classification of turbines with the optimum spanning tree and determined midpoints for each group. In Figure 17, cabling design using the proposed method and types of cables are depicted. Sixty-eight turbines have been considered for this wind farm.

To prove the effectiveness of the proposed method, the results have been compared with four other cases considering the same number of turbine. In method A, which is shown in Figure 18, the dominant direction of wind and wake effect has been investigated. In this method, wake effect cannot be modeled sufficiently because different directions of wind have not been considered. In addition, the costs of roads and collector have not been considered. In method B, shown in Figure 19, the majority of turbines have been placed close to the roads to minimize the cost of roads. In this method, the wake effect and type of cables have not been considered.

Figure 20 illustrates method C in which the turbines are distributed in the whole area of wind farm to reduce the wake effect. Method D, shown in Figure 21, is based on the classification of turbines and the type of cables. The main purpose of this method is minimizing the cables current. The results of comparison among the proposed method and the aforementioned methods are given in Table 3.

For optimization, the objective function should be minimized. The more objective function is minimized, the more optimal solution is obtained.

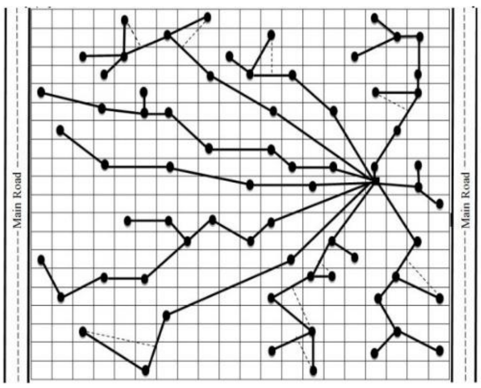


Figure 16. Classification of turbines considering spinning tree for each group and finding the midpoints

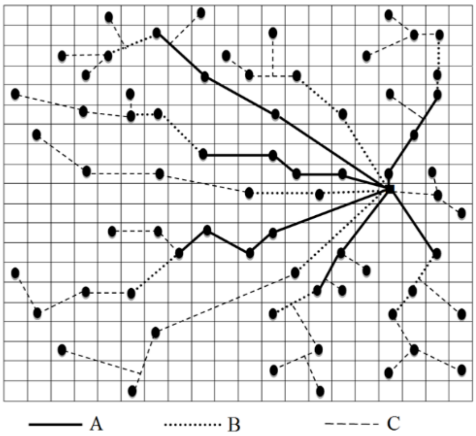


Figure 17. Cabling according to the proposed method and the type of used cables

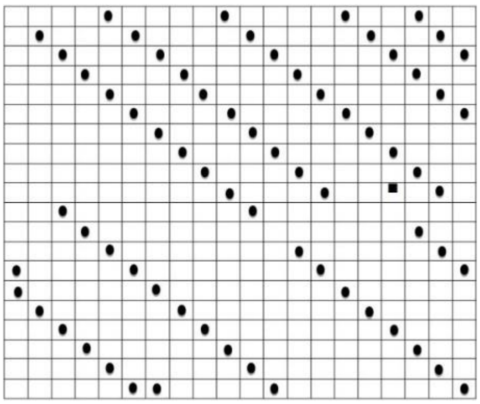

Figure 18. Wind turbine sitting method A

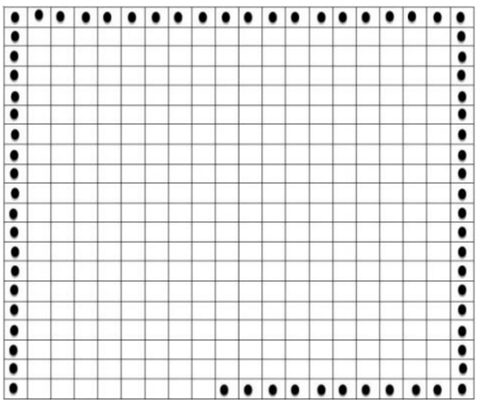

Figure 19. Wind turbine sitting method B

As can be seen in Table 3, when the proposed method is implemented, the total objective function which includes all objectives is optimized significantly. Although each method may have good results for one objective, the proposed method satisfies all objective remarkably. Therefore, using the proposed method in the real cases can help the wind farm designers to save the money and increase the extracted energy.

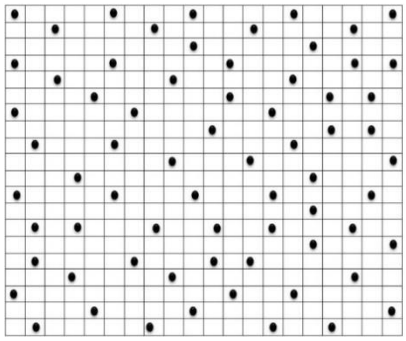

Figure 20. Wind turbine sitting method C

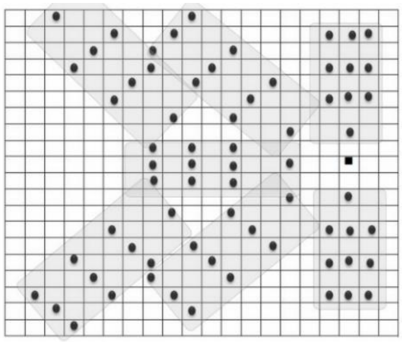

Figure 21. Wind turbine sitting method D

Table 3. Comparison of different sitting methods in the wind farm

| | Objective function | Total annual energy (kWh) |
|---|---|---|
| The proposed method | 658.32 | $2.6293\times 10^5$ |
| Sitting method A | 725.01 | $2.4938\times 10^5$ |
| Sitting method B | 698.59 | $2.1568\times 10^5$ |
| Sitting method C | 791.73 | $2.6663\times 10^5$ |
| Sitting method D | 768.27 | $2.1729\times 10^5$ |

## VIII. CONCLUSIONS

In this paper, a method was proposed to optimally find the best positions for wind turbines in a wind farm. The study was carried out to maximize the annual energy by reducing the wake effect. Furthermore, in the positioning road construction and cabling cost were considered. To have a real case, the Mil Nader region was selected for study and the annual wind data with ten-minute interval was used for simulation. Genetic algorithm was implemented for the optimization of this problem. The results of proposed method, compared with other methods, show that this method has high efficiency.

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