Optimal Planning of Wind Farm Layout and Integration to Electric Grid Infrastructure

Daniela I. Borissova[1,2], Ivan C. Mustakerov[1]
1 – Institute of Information and Communication Technologies at Bulgarian Academy of Sciences, Sofia, Bulgaria.
Email: dborissova@iit.bas.bg (Corresponding author)
2 – University of Library Studies and Information Technologies, Information Systems and Technologies, Sofia, Bulgaria.
Email: mustakerov@iit.bas.bg

Received: June 2017 Revised: July 2017 Accepted: August 2017

ABSTRACT

To meet increased demand in energy while reducing greenhouse gas emissions, different renewable energy technologies are used. The wind power provides potential benefits as it is a clean, renewable, economic and domestically available power source. Building of sustainable wind farm is subject on many different factors. The aim of the paper is to contribute optimal turbines placement and integration to the electrical grid. For this goal, a mixed-integer non-linear optimization model for determination of maximum wind farm capacity is defined. Another linear optimization model is used to determine the minimum distance of wind turbines in the farm to the point of common coupling. The proposed approach is tested numerically for particular wind turbines type and given wind farm area. The testing results demonstrate the applicability of the proposed optimization models for determination of maximum wind farm capacity and minimum distance between wind farm and point of common coupling.

KEYWORDS: Grid Integration, Optimal Planning, Wind Farm Layout Design.

1. INTRODUCTION

The optimal planning of renewable resources and their connection in grid of electric infrastructure brings up new challenges to the decision makers. Due to the technical advances, the wind power has become a competitive alternative generation source. Developers and financiers such as stakeholders have to evaluate technically wind farm project to determine its profitability and feasibility. A key issue is the layout of wind turbines that directly has influence on the efficiency of wind farm and is an essential part in layout designing, where the optimal placements of turbines has to be determined. These optimal placements of turbines affect both cases of onshore and offshore wind farms. The goal is to maximize the efficiency of wind farm by proper design approaches. Designing of renewable energy system can be represented as a problem for placement of turbines within area with known dimensions and known wind conditions. Many investigations are on subject of wind farm layout proposing different approaches. Some of the recent approaches use multi-objective optimization and mathematically reasoned group decision making [1]. The complexity of wind farm design can be approached by using custom optimization software [2] or can be preliminary assessed by software tools [3]. The designing of wind farm layout can be done by means of evolutionary algorithms [4], by genetic algorithm [5] or by mixed integer programming [6-7]. Some approaches involve forbidden areas where for different reasons it is not possible to place turbines [8-11].

The development of wind farm requires land with sufficient wind resources, proximity to the power grid, and compatibility with environmental and regulatory requirements [12]. At early stages of high strategic level, detailed analysis of wind farm planning, clustering and connection to grid is needed [13]. There are number of factors that contribute to uncertainty in estimation of costs for connection to grid as: land and construction, overhead or underground transmission, needed upgrades between generation and distribution system, length of upgrades, scale and scope in transmission expansion [14]. The costs of different industrial wind farm investigations show that 60-80% of the overall investment costs constitute of the installed wind turbines price [7]. That means of 20-40% of investment is for infrastructure and any possible decrease of connection costs will be beneficial.

In this paper, the problem of wind farm layout optimization is discussed in respect to integration to electric grid infrastructure. For this goal, a methodology, which first finds the best layout with regard to wake effect and then choose the best positions from possible places with regard to point of common coupling distance from each turbine is proposed. Two mathematical models are proposed and involved in methodology: 1) mixed-integer nonlinear optimization model for determination of the optimal wind turbines number and layout, and 2) linear optimization model for determination of location of given number of turbines for which the distances to the point of common coupling are minimal.

2. PROBLEM DESCRIPTION

Building of sustainable wind farm is subject on many factors that could be summarized as follows: 1) determination of suitable wind area with enough wind resources; 2) selection of most appropriate wind turbine type in accordance to the wind conditions; 3) calculation of maximum capacity of wind farm considering wind conditions and wind turbine type parameters; 4) determination of number of wind turbines to be placed with the farm to meet the required capacity; and 5) determination of positions where wind turbines are to be placed considering existing infrastructure of electrical power lines if any. The flowchart of stages to start wind farm project are shown in Fig. 1.

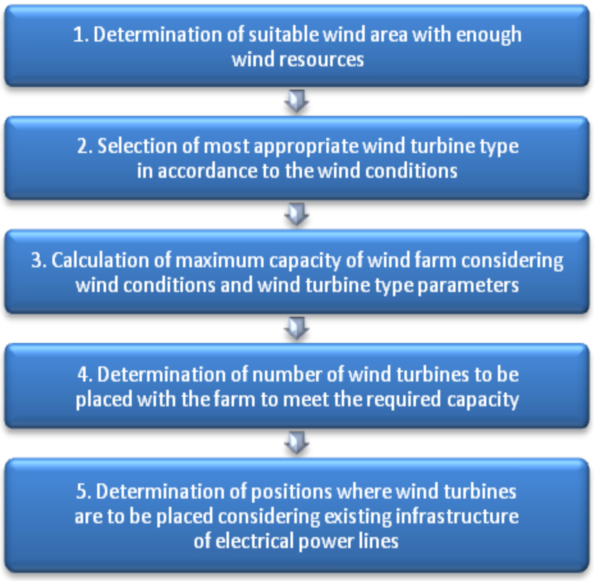

Fig. 1. Flowchart of stages of wind farm project

The major contribution in the paper emphasizes on the stages 3 and 5 where maximum capacity of wind farm is to be calculated and the optimal positions of wind turbines are to be determined considering the existing infrastructure of electrical power lines. Both of these problems are approached by using mathematical programming techniques for optimization.

3. OPTIMAL PLANNING OF WIND FARM LAYOUT AND INTEGRATION TO ELECTRICAL GRID

Determination of proper area for wind farm is subject to long term investigations. When this area is approved, the most appropriate wind turbine type has to be chosen in accordance to the wind conditions. Different approaches could be used to calculate the maximum capacity of wind farm taking into account wind conditions and parameters of wind turbine type [4-7]. The local authorities are essential factor for determination of number of wind turbines to be placed within the farm and to make realization of the project possible. Considering all of these, the optimal positions of wind turbines to be placed can be determined considering existing infrastructure of electrical power lines.

3.1. Optimization Model for Maximum Wind Farm Capacity Determination

This section describes the step 3 of the proposed flowchart (Fig. 1). The maximum of capacity of wind farm means to place as much as possible turbines within given area considering the wind conditions, wind turbine parameters and criterion for minimum cost per unit of annual energy. This requires determining of closely spaced positions of turbines in array. The main obstacle to place the turbines closely is due to the existence of so called wake effect. Wake effect is one of the significant problems in the wind farms, which increases the power loss if turbines are too closely located to each other [15]. The wake effect is taken into account by using optimal spacing limits for distances between turbines depending on wind conditions [8], [16]. Due to the stochastic nature of the wind, genetic and metaheuristic algorithms are used to design wind farm layout [5], [8], [9]. The other approach to tackle with stochastic nature is by using optimal spacing distances depending on the speed and direction of the wind. The separation distances between turbines in columns contribute to avoid the negative influence of wake effect and can be determined by means of separation coefficients expressed in turbine rotor diameters.

The optimization model for determination of maximum wind farm capacity considering particular wind turbine type and using the utility function for costs per unit of energy produced over the year is as follows:

$$\min \frac{N\left(\frac{2}{3}+\frac{1}{3}\exp(-0.00174N^{2})\right)}{NP_{wt}h_{y}\eta} \qquad (1)$$

subject to

$$N = N_x N_y \qquad (2)$$

$$N_x = (L_x/S_x) + 1 \tag{3}$$

$$N_y = (L_y/S_y) + 1 \tag{4}$$

$$S_x = k_x D_{wt} \tag{5}$$

$$S_y = k_y D_{wt} \tag{6}$$

$$k_y^{\min} \le k_y \le k_y^{\max} \tag{7}$$

$$k_x^{\min} \le k_x \le k_x^{\max} \tag{8}$$

The used relation for representing the costs of large wind farm $N\left(\frac{2}{3}+\frac{1}{3}\exp(-0.00174N^2)\right)$ as a function only of number of turbines N [8], make it possible to get a preliminary estimation for the costs of entire farm per year. The annual energy production $NP_{wt}h_y\eta$ is expressed also by number of turbines, rated power of wind turbines type, number of hours over the year h_y and nominal utilization coefficient η [17]. The objective function (1) provides an estimation of produced energy over the year from wind farm in costs per unit energy dimension. This value can be used as a measure for wind farm effectiveness. Total number turbines N is represented by number of turbines in rows N_y and columns N_x. Wind turbine rotor diameter is denoted by D_{wt}. The rectangular wind site has dimensions expressed as L_x and L_y. The decision variables in the model (1) – (8) are N, N_x and N_y. The equations (3) and (4) determine the number of turbines in columns and rows taking into account the dimensions L_x and L_y of the site area. The separation distances S_x and S_y are expressed by separation coefficients k_x and k_y considered also as variables within boundaries (7) and (8) in regard to the wind conditions. Depending on the wind speed and directions, the wind turbines separation distances in prevailing wind direction are within the range of 6 to 12 rotor diameters and for opposite direction from 1.1 to 3 rotor diameters, while in case of uniform wind directions both distances are equal to 5 rotor diameters [8], [16].

The maximum capacity of wind farm that conform the criterion for minimum cost per unit of annual energy is determined by the total turbines number taking into account separation distances between turbines needed to overcome the wake effect. This corresponds to the step 4 from the flowchart (Fig. 1). The determined number of turbines by solution of optimization problem (1) – (8) is the maximal number according to the input data.

In reality, the number of turbines constituting the wind farm is subject to determination by local authorities and stakeholders according to the existing power needs. In most cases, the power needs required smaller number of turbines then determined maximal one by formulated optimization problem (1) – (8).

3.2. Optimization Model for Determination of Wind Turbines Placement Considering Location of Point of Common Coupling

The integration of renewable energy is a result of increasing energy demand and is related with reducing greenhouse gas emissions. A challenging problem is related to connection with electrical grid to get the optimal distance between wind farm and grid and to decrease the transmission costs.

The determination of maximum wind farm capacity defines optimal locations of turbines. On the other hand, the number of wind turbines determined by local authorities and stakeholders are fixed and need to be placed in some of determined optimal turbines locations. This number of turbines should be located so that the distances between turbines and the point of common coupling are minimal. For the goal, an optimization model considering existing position of the point of common coupling is defined:

$$\min \sum_{i,j} x_{ij} r_{ij} \tag{9}$$

subject to

$$\sum x_{ij} = N_{wt} \tag{10}$$

where x_{ij} are binary integer variables, r_{ij} are distances from turbines to the point of common coupling, N_{wt} is the number of turbines to be placed with farm.

The objective function (9) seeks to determine such positions of turbines for which the distances r_{ij} to the point of common coupling is minimal. The binary integer variables x_{ij} are assigned to all possible turbines locations determined from the solution of optimization problem (1) – (8). The number of turbines to be placed is expressed by N_{wt}.

4. NUMERICAL TESTING

This section illustrates the applicability of the described optimization techniques for problems related to the positioning of wind turbines and considering the existing infrastructure.

4.1. Solving the Problem for Maximum Wind Farm Capacity Determination

The dimensions of considered wind farm area is given with rectangular shape determined by $L_x = 4\ km$ and $L_y = 2\ km$. The given input data about wind conditions are prevailing wind direction parallel to the longer side of the rectangular shape. The separation coefficients needed to overcome the negative wake effect according to the given wind conditions are limited within the range of $7.8 \le k_x \le 9.5$ for prevailing wind direction and $1.3 \le k_y \le 2.2$ for opposite wind direction. The selected turbine type for the investigated wind farm has been rated power of 3.6 MW and rotor diameter of 107 m. The nominal utilization coefficient

η in the case is given to be equal to 0.32. The hours over the year h_y are 8760 (calculated as 365*24).

Using these input data, the optimization problem (1) – (8) determines value for the objective function (1) equal to $0.6648839.10^{-4}$ in unit of costs per MWh per year. The rest of the parameters of wind farm with theoretically possible maximum capacity are shown in Table 1.

Table 1. The parameters of wind farm for maximum capacity.

P_{wt}, MW	D_{wt}, m	L_x, km	L_y, km	N	S_x, m	S_y, m	k_x	k_y
Input data				Data from solution				
3.6	107	4	2	50	1000	222.2	9.35	2.07

The positions of turbines of the same type that ensure maximum capacity of wind area under minimum cost per unit of annual energy production are illustrated in Fig. 2.

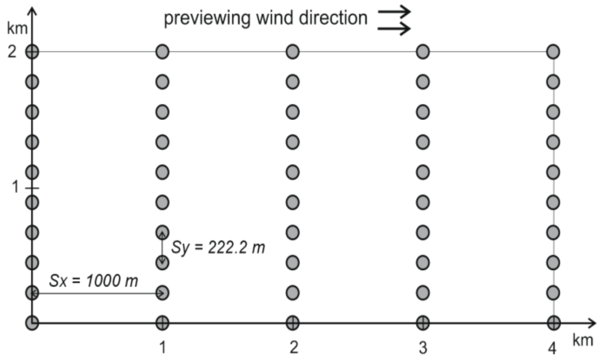

Fig. 2. Layout of turbines for maximum wind farm capacity under minimum cost per unit of annual energy

These optimal positions will be used to select some of them where to place the given fixed number of turbines so that distances to point of common coupling are minimal.

4.2. Determination of Positions of Given Number of Wind Turbines Considering Location of Point of Common Coupling

It is assumed that the number of turbines to constitute the new wind farm is $N_{wt} = 44$ turbines. From the determined 50 maximal possible locations for turbines determined as described in section 4.1, 44 of these turbines locations need to be selected. The selected locations have to satisfy the optimization model (9) – (10) where the distances from each turbine to the point of common coupling are minimal. Fig. 3 illustrates the position point of common coupling and locations of 44 turbines as a result of solution of optimization problem (9) – (10).

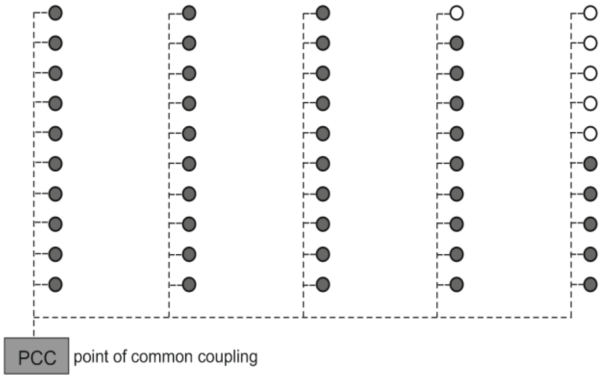

Fig. 3. Optimal positions for 44 wind turbines considering location of point of common coupling

This solution determines that binary integer variables for turbines location $x_{4,10}$; $x_{5,6}$; $x_{5,7}$; $x_{5,8}$; $x_{5,9}$ and $x_{5,10}$ are equal to 0. The rest 44 binary integer variables are determined to be equal to 1.

In this case, the solution determines zero values for variables $x_{1,8}$; $x_{1,9}$; $x_{1,10}$; $x_{5,8}$; $x_{5,9}$ and $x_{5,10}$. The rest 44 variables are equal to 1, i.e. these variables define best locations of wind turbines according to minimal distances to point of common coupling.

If the location of point of common coupling has other position as shown in Fig. 4, then the optimal locations for placement of 44 turbines are different.

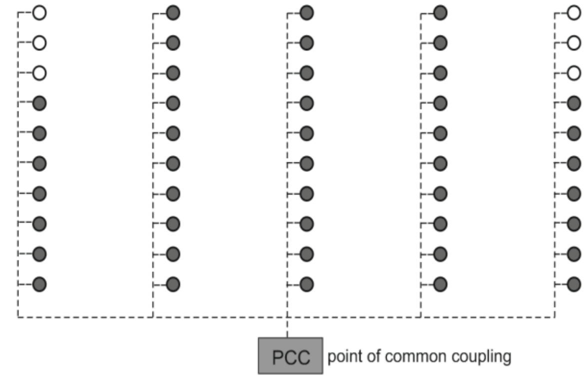

Fig. 4. Optimal positions for 44 wind turbines considering location of point of common coupling

5. RESULT ANALYSIS AND DISCUSSION

Formulated optimization tasks based on the mixed-integer non-linear optimization model (1) – (8) and linear optimization model (9) – (10) were solved by means of LNGO software [18] on PC with Intel Core i3 @ 2.93 GHz under MS Windows. The solution times for both tasks are about a second.

Formulated mixed-integer nonlinear optimization model (1) – (8) determines the maximum number of wind turbines in array considering the wake effect, particular turbine type and land area dimensions according to the utility function for costs per unit of energy produced over the year. This objective function can be replaced with any other reasonable one if is needed to take into account other specific considerations. The second linear optimization model (9) – (10) determines only these locations of turbines for which the overall distance to the point of common coupling is minimal. This means that the position of point of common coupling must be carefully considered in advance because it influences the selecting of locations of the turbines in the farm (see Fig. 3 and Fig. 4). In both cases, the testing results show applicability of the proposed approach based on the defined optimization models.

The proposed approach can be used in conjunction with others methods for determination of maximum wind farm capacity and other objective function/s.

6. CONCLUSION

In this paper, an approach to wind farm layout optimization in respect to integration to electric grid infrastructure is discussed. A methodology involving the needed stages to start wind farm project is proposed. It includes mixed-integer nonlinear optimization model for determination of the optimal wind turbines number and their layout, and linear optimization model for determination of location of given number of turbines for which the distances to the point of common coupling are minimal.

The proposed methodology is numerically tested and obtained results demonstrate the applicability and functionality of the used optimization models. The described techniques for optimal planning and building of wind farm could be used for other renewable energy sources too. As a future development, this approach can be modified to reflect other requirements for integration to infrastructure of electrical grid.

REFERENCES

[1] D. Borissova, I. Mustakerov. "**Two-stage placement algorithm with multi-objective optimization and group decision making**." *Cybernetics and Information Technologies*, Vol. 17(1), pp. 87-103, 2017.

[2] D. Borissova, I. Mustakerov. "**A framework for designing of optimization software tools by commercial API implementation**." *Int. Journal of Advanced Engineering, Management and Science*, Vol. 2(10), pp. 1790-1795, 2016.

[3] D. Borissova, I. Mustakerov. "**Web-based tool for preliminary assessment of wind power plant design**", *in Proc. of 4th International Conference on Information Systems and Technologies (ICIST 2014)*, Valencia, Spain, pp. 139-149, 2014.

[4] A. Kusiak, Z. Song. "**Design of wind farm layout for maximum wind energy capture**". *Renewable Energy*, Vol. 35(3), pp. 685-694, 2009.

[5] G. Mosetti, C. Poloni, and D. Diviacco. "**Optimization of wind turbine positioning in large wind farms by means of a Genetic algorithm**". *Journal of Wind Engineering & Industrial Aerodynamics*, Vol. 51, pp. 105-116, 1994.

[6] I. Mustakerov, D. Borissova. "**Wind park layout design using combinatorial optimization**." in *Wind Turbines*, I. Al-Bahadly, Ed. In Tech, pp. 403-424, 2011.

[7] D. Borissova, I. Mustakerov. "**A generalized combinatorial optimization approach to wind power plant design**." *Cybernetics and Information Technologies*, Vol. 10(4), pp. 62-74, 2010.

[8] S. A. Grady, M. Y. Hussaini, and M. M. Abdullah. "**Placement of Wind Turbines Using Genetic Algorithms**". *Renewable Energy*, Vol. 30(2), pp. 259-270, 2005.

[9] J. Serrano-Gonzalez, A. G. Gonzalez-Rodriguez, J. Castro-Mora, J. Riquelme-Santos, and M. Burgos-Payan. "**Optimization of wind farm turbines layout using an evolutive algorithm**". *Renewable Energy*, Vol. 35, pp. 1671-1681, 2010.

[10] J. Serrano-Gonzalez, A. G. Gonzalez-Rodriguez, J. Castro-Mora, J. Riquelme-Santos, and M. Burgos-Payan. "**Overall design optimization of wind farms**". *Renewable Energy*, Vol. 36, pp. 1973-1982, 2011.

[11] D. Borissova, and I. Mustakerov. "**Wind power plant layout design and assessment considering forbidden zones for location of turbines**." *Int. Journal of Advanced Modeling and Optimization*, Vol. 19(1), pp. 29-38, 2017.

[12] L. C. Rodman, R. K. Meentemeyer. "**A geographic analysis of wind turbine placement in Northern California**". *Energy Policy*, Vol. 34, pp. 2137-2149, 2006.

[13] H. G. Svendsen. "**Planning tool for clustering and optimised grid connection of offshore wind farms**". *Energy Procedia*, Vol. 35, pp. 297-306, 2013.

[14] **The Full Cost of Electricity (FCe-): Executive Summary: The Full Cost of Electricity**. A Series of White Papers, pp. 1-31, 2016.

[15] R. Shakoor, M. Y. Hassan, A. Raheem, and Y. K. Wu. "**Wake effect modeling: A review of wind farm layout optimization using Jensen's model**". Renewable & Sustainable Energy Reviews, Vol. 58, pp. 1048-1059, 2016.

[16] G. Smith, W. Schlez, A. Liddell, A. Neubert, and A. Pena. "**Advanced Wake Model for Very Closely Spaced Turbines**", *in Proc. EWEC* 2006, Athens. 2006.

[17] I. Mustakerov, and D. Borissova. "**Wind turbines type and number choice using combinatorial optimization**", *Renewable Energy*, Vol. 35(9), pp. 1887-1894, 2010.

[18] LINDO Systems Inc., http://www.lindo.com/