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OPTIMAL RECONFIGURATION OF A WIND FARM POWER DISTRIBUTION NETWORK

BY

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Abstract. The investments in power transmission and distribution networks are essential for renewable power generation implementation. The wind farm topology means the combined electric power sources (wind turbine) and branching lines. Taking into account that branching lines for a wind farm are underground power lines (cable), in this paper a two stage approach to optimize the electrical inter-array cable systems was proposed. The proposed approach is compatible with both radial and branched design philosophies, and can be optimized for total cable length or cable cost. The novelty of the approach is based on a combination of classical and met-heuristic algorithms for wind farm topology optimization. The results of case study clearly demonstrated the feasibility of the proposed method and showed that it can be used as a reliable tool in off-shore wind farm design for optimal topology determination.

Key words: wind farm; graph theory; ant colony optimization.

1. Introduction

In today's world we can clearly see that the investment in electric energy transmission and distribution infrastructures is very important for the power industry (Neagu *et al.*, 2013). Generally, network configuration represents internal construction nodes and lines. The wind farm network structure means the combined power sources (wind turbine) and branching lines. In a wind farm the branching lines are generally represented by underground lines (cables). An

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early approach of wind farm topology optimization or optimal collector system design (OCSD), which is a young field of research, is using a clustering method (Dutta *et al.*, 2011). Other approaches for OCSD include a mixed-integer programming based formulation proposed in (Hertz *et al.*, 2012; Fagerfjäll, 2010; Donovan, 2006), a standard genetic algorithm in (Zhao *et al.*, 2009), a hybrid genetic and immune algorithm in (Dong *et al.*, 2008) and a multi-objective evolutionary strategy considered in (Kusiak *et al.*, 2010). All of these studies led to a wind farm layout cost minimization.

One can automatically allocate wind turbines to the nearest stations and obtain the topology structure of cables used to connect wind turbines or the turbine and step-up station. In a wind farm, the turbines are connected to a transformer by cable routes which cannot cross each other. Finding the minimum cost array cable layout thus amounts to a minimum spanning tree (MST) problem with the additional constraints that the routes must be embedded in the plane. For this problem, both exact and heuristic methods are of interest (Bauer *et al*., 2014).

This paper approach was applied for wind farm topology optimization, being compatible with both radial and branched design philosophies, and can estimate the total cable length or can do cost optimization. Global optimization of this problem is considered mathematically impossible and the method is adapted to provide a local optimal solution in a useful amount of time. In this way, it enables fast estimation of different design configurations while continuously improving the electricity system layout design process (Jenkins *et al*., 2013).

This paper is structured as follows. First, the state of the art of the problem is concisely reviewed. Then, the mathematical model of proposed electrical cable route optimization is presented. After that, the methodologies applied into the proposed model will be described, together with the implementation details. Finally, the numerical simulations, the results and conclusions extracted by discussing the proposed methods are presented. The results of case study clearly demonstrated the feasibility of the proposed method and showed that it can be used as a reliable tool in off-shore wind farm design for optimal topology determination.

2. Problem Formulation

The topology optimization problem is known in literature as a problem of total cost minimization or minimum spanning tree (MST) (Montoya *et al*., 2012). A minimalist formulation of the mathematical model for tree networks route optimization problem is the following: by knowing the nodes (step-up station and wind turbines) location in Cartesian coordinates, the minimum cable route length can be determined. Based on numerous methods for the synthesis of the optimal networks configuration, the MST problem (minimum length distribution network) can be formulated. In literature, the MST setting is a typical combinatorial optimization problem, and can be solved using various deterministic methods (Greenberg, 1998; Sudhakar *et al*., 2010; Neagu *et al*., 2013) or methods based on artificial intelligence algorithms (Zhou *et al*., 2010).

In order to optimize the tree networks routes, the proposed mathematical model includes two steps, namely: first step is the optimal wind farm cable route construction using a single source node (step-up station) and all wind turbines; second step optimizes the length of cable route resulting in a minimum by introducing an arbitrary number of additional nodes in the solution of the first step. The novelty of the paper consists in using the common ant colony optimization (metaheuristic) algorithm adapted to graph theory for optimal cable route determination and the Steiner tree method (Avella *et al*., 2005) for reconfiguration of the wind farm cable route.

2.1. Optimal Topology Construction Using the a Met-Heuristic Algorithm

Ant colony optimization (ACO) paradigm is included in relatively recent intelligent agents, based on ants biological behavior. By tracking the ants behavior in nature, is found that they can find the shortest path from the anthill to a food source in absence of visual information without direct communication between them; the same ants can adapt to environmental changes and ACO tries to use real ant skills to solve the optimization problems. This paragraph presents an ACO particular approach (Fig. 1), adapted from graph theory for wind farm optimal cable route determination. The solution uses a graph with n vertex and all edges between these. Each edge (i, k) of complete graph is associated with a pheromone concentration, used for the route selection by the ant from the colony. Initially, the pheromone concentration is set to small positive values (*i.e*. 0.01). In the ACO algorithm shown in Fig. 1 the minimum route length was initialized with a high value. The numbers of ants will be distributed as evenly as possible between the graph vertices. In the next step is admitted that the number of vertices and the number of ants is chosen, while in each node will distribute the total number of ants reported to the all network nodes.

1. Initial data.
2. General initialization.
3. Select the location nodes for each ant, using a random function.
4. Insert the first node (current node) in tabu list of each ant.
5. Set the current node position in tabu list: s=1.
6. Establish topology (completing tabu lists).
7. Select the minimum length cable network.
8. Update pheromone concentrations on the graph edges.
9. Build the minimum tree from obtained trees by each ant.
10. Displays the total minimum length tree.
End algorithm.

Fig. 1 – The ACO pseudo-code adapted for considered problem.

According to the proposed problem the optimization process contains the restriction that an ant must pass through each node without forming cycles. Each ant route selection is done in tabu list, which contains the elements that describe the sequence of visited nodes (vertices). After the ant’s distribution in the graph nodes, the tabu list assigned to each ant will initialize the first position with the order number of the node where that ant was distributed.

Further, the ants should move in different graph nodes, until the tabu lists are complete, each ant making a complete graph tour. In another step, for every ant the destination node should not be included in tabu list, being determined by computing probabilities using the following expressions:

$$P_{ik} = \begin{cases} \dfrac{(\tau_{ik})^{\alpha}(1/d_{ik})^{\beta}}{\sum\limits_{p \notin Tabu_j} (\tau_{ip})^{\alpha}(1/d_{ip})^{\beta}}, & k \notin Tabu_j; \\ 0, & k \in Tabu_j. \end{cases} \tag{1}$$

From the previous equation can see that from all k nodes where is allowed the movement from the node i, will be select node k^*, where the probability ($P_{ik}*$) becomes the highest. Therefore, the ant j will move to node k^* ($Nod_j = k^*$) and k^* will be introduced in tabu list ($Tabu_j(s) = k^*$). Regarding the terms α and β from (1), they control the percentage of pheromone concentration (τ_{ik}) and visibility ($1/d_{ik}$) to establish the probability. If $\beta = 0$, the P_{ik} probabilities only depend on the pheromone concentration. Also, if $\alpha = 0$ the P_{ik} probabilities only depend on the nodes visibility (distance between nodes). When all the ants have passed through all the graph nodes, each ant route is closed without returning to the origin node. Practically, this aspect is the ACO algorithm adaptation to the studied problem. Further, according to the algorithm shown in Fig. 1 the route lengths for all the ants' must be calculated and will store the minimum length, which coincides with the final iteration. Before switching to another step, the pheromone concentration must be updated on each graph edge by using:

$$\tau_{ik} = \rho\tau_{ik} + \Delta\tau_{ik}, \tag{2}$$

where: ρ is a subunit coefficient, from which it results the pheromone evaporation rate on the established routes $(1 - \rho)$.

Coefficient ρ always choose subunit (ρ = 0.1), because should be avoided unlimited accumulation of pheromones on the graph edges. $\Delta\tau_{ik}$ represent the pheromone concentration correction on the edge (i, k) determined by the total ant number which moved from the node i to k, using the equation:

$$\Delta\tau_{ik} = \sum_{j=1}^{na} \Delta\tau_{ik}^{j}, \tag{3}$$

where: $\Delta\tau_{ik}^{j}$ from (3) represents the deposited pheromone quantity on edge (i, k) by ant j, determined as follows:

$$\Delta\tau_{ik}^{j} = \begin{cases} \dfrac{Q}{L_j}, \text{ if } i,k \in Tabu_j \text{ and } i = Tabu_j(p);\ k = Tabu_j(p+1); \\ 0, \text{ otherwise.} \end{cases} \tag{4}$$

Stopping criterion coincides with the maximum number of iterations (T_{max}). While $t < T_{max}$, reset tabu lists of the ants and the procedure is restarted by resetting first element of every tabu list with current node number where each ant are located. ACO algorithm is (Neagu *et al.*, 2014): natural; parallel and distributed; cooperative; versatile; robust.

2.2. Wind Farm Cable Route Reconfiguration

In the literature, the minimum network length determined by the union of the system formed by initial nodes (generally known) and an arbitrary number of nodes newly introduced is known as the generalized Steiner problem (Neagu *et al.*, 2013). Considering these aspects, the minimum length tree from all trees with additional nodes is called minimal Steiner tree, which results at the searching process among all trees that can be obtained based on all possible combinations of initial and additional nodes. Of course, these trees types are numerous, their number is $(n + l)^{n + l + 2}$, where n represents the initial number of nodes and l is the additional number of nodes.

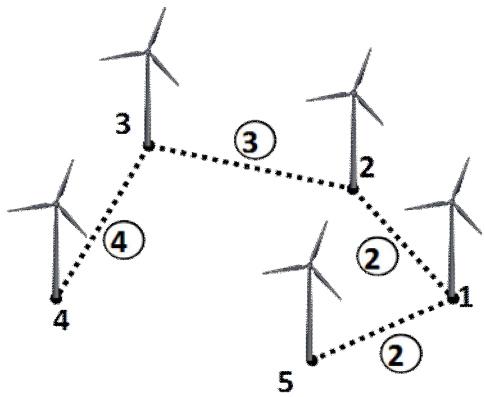

Fig. 2 – Example of a minimum length of a wind farm cable route.

For example in a wind farm, if the step-up station is known, the proposed algorithm is carried out starting from this one. Fig. 2 presents an example of five minimum tree cable route configurations, and can easily observe that a new additional branching node allows a tree with a total length less than aforementioned. For example, Fig. 3 illustrates a tree formed by three nodes, arranged in an equilateral triangle vertex.

The wind farm minimum cable length construction methods, using the Steiner points, form a whole class of methods based on the properties of Steiner trees, namely: i) The branches that connect the initial nodes with the Steiner points are arranged at 120 degrees angles. ii) One Steiner point corresponds to three vertices (nodes); theoretically, the number of Steiner points is unlimited ($0 \leq k \leq n - 2$). iii) Best solution is for a network with at least three nodes and one Steiner point. Hereinafter the Steiner tree construction using the so-called Euclidean constructions is presented in Fig. 4

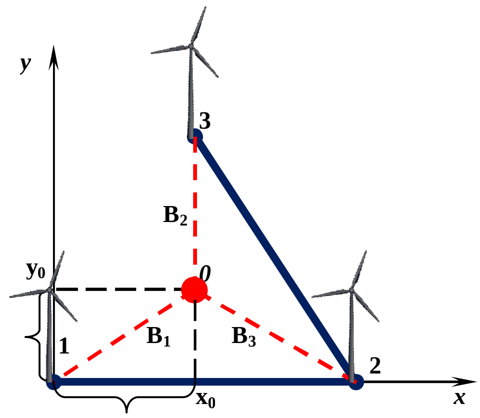

Fig. 3 – Wind farm cable route reconfiguration using Steiner points (*0*).

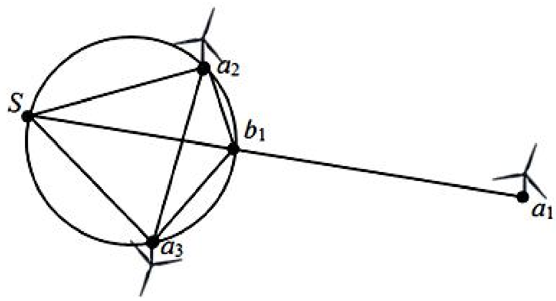

Fig. 4 – Euclidian construction of the Steiner tree.

For the wind farm with initial wind turbine a_1, a_2, a_3 is necessary an additional point, b_1. This point will coincide with one of the given points if any defined angle by the nodes is greater or equal with 120º (if the angle $a_2a_1a_3 \geq$ ≥ 120º, then b_1 coincides with a_1); if all angles are less than 120º, then b_1 is found within the triangle formed by a_1, a_2, a_3 vertices.

The Euclidean construction is obtained as follows: by using one of the branches, for example a_2a_3, an equilateral triangle is formed and the peak *S* is situated in opposition to a_1 node in the a_2a_3 edge. Point b_1 will be situated on the circumscribed circle of the triangle. In this case, the Steiner point is situated at the intersection of the circle with the right point Sa_1 called the equivalent of the a_2 and a_3 nodes. The main steps of the minimum length of wind farm interconnection cable (the optimal route from the economic point of view) in all Steiner method variants are the following:

i) The initial set of nodes is decomposed into subsets which allow Steiner tree construction (for problem size reduction).

ii) For each subset of nodes, using the described procedure a Steiner tree topology is obtained.

iii) Minimum tree length is obtained by aggregating the separate subsets.

3. Wind Farm Topology Reconfiguration

The choice of economic indicators for different variants estimation of wind farm cable route optimization depends on the problem to be solved and the particular characteristics of each design level. Here can also be included the values of total updated expenses, total investment, energy losses, operating costs voltage drops, damages caused by the unpowered consumers, etc.

Radial or branched wind farm cable route synthesis problem is divided in two stages: one uses ACO algorithm building the minimum cable route length and the second improves the network by adding supplementary branch nodes. The wind farm structure or cable route improvement can be achieved by shifting the source nodes to the ends and vice versa, with the particularity that the latter would be preferable because the ends power flows are known.

By using the mathematical model described above, a wind farm arborescence cable route optimization application was developed. The application uses a combination of ACO and Steiner algorithms for which the goal function is the minimum cable route length (between wind turbines and the step-up station) with radial structure restrictions. The proposed approach contains the following steps:

a) Input data: general data (step-up station and all wind turbines); consumers data (Cartesian coordinates, wind turbine name); the step-up station is always first.

b) Determining the minimum cable route length with ACO algorithm (minimum lenght of the wind farm configuration).

c) Steiner algorithm application on resulted wind farm cable route from the previous step, by additional branch nodes introduction (Steiner points). Another reduction of wind farm cable route length through reconfiguration.

d) Display the partial results (total network length) for the current version, in order to select the optimal variant. Finally, display the wind farm topology and the global minimum cable route length.

4. Study Case

To highlight the utility of the double-step approach proposed in the paper, for optimal cable route determination, a wind farm with 77 wind turbine was analyzed. In this context, input data of test wind farm distribution with 80 nodes (the three step-up stations are marked with red) is presented in Fig. 5 (Chen *et al*., 2013).

In first step, based on aforementioned methodology, using a successive search technique (ACO), the wind farm cable route length results to be 29,580 m, with the configuration presented in Fig. 6.

By optimizing minimum graph length obtained using ACO, in a second step, to allow new route construction, 26 additional Steiner points are needed, and the minimum wind farm cable route length resulted is of 28,014 m (Fig. 7).

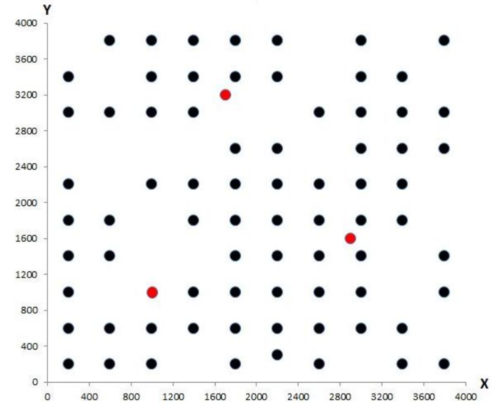

Fig. 5 – The positioning of wind turbine in the analysed wind farm.

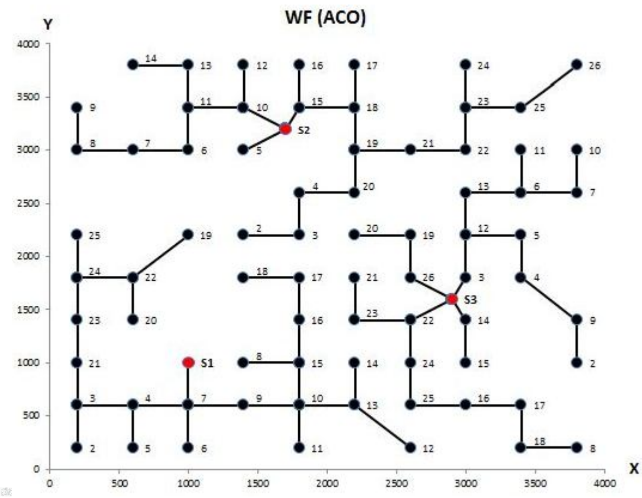

Fig. 6 – Wind farm cable route optimization using ACO algorithm.

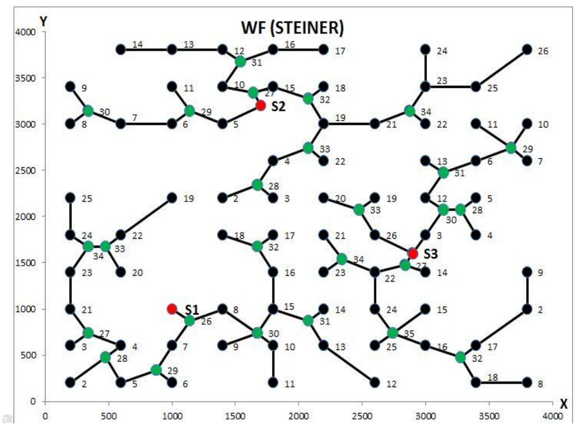

Fig. 7 – Wind farm cable reconfiguration using steiner points.

We need to mention that these branching points are not involving any additional cost because we are referring to underground power cables route from a wind farm. The additional Steiner points are summarized in Table 1 for the three areas in the following format: additional node number, the Cartesian coordinates and the three nodes which could form the Steiner branch point.

Table 1
Additional Branch Points (*Steiner Points*) *Necessary in the Analysed Wind Farm*

Number of Steiner points	Cartesian coordinates		Nodes which form the Steiner point		
	X, [m]	*Y*, [m]			
Substation S1					
26	1,140	875	1	7	8
27	340	740	3	4	21
28	475	475	3	4	5
29	875	340	5	6	7
30	1,675	750	9	10	15
31	2,075	875	13	14	15
32	1,675	1,675	16	17	18
33	475	1,675	20	22	24
34	340	1,675	22	23	24
Substation S2					
27	1,640	3,340	1	10	15
28	1,675	2,340	2	3	4
29	1,140	3,140	5	6	11
30	340	3,140	7	8	9
31	1,540	3,675	10	12	16
32	2,075	3,275	15	18	19
33	2,075	2,740	4	19	20
34	2,875	3,140	21	22	23
Substation S3					
27	2840	1475	1	14	22
28	3275	2075	4	5	12
29	3675	2740	6	7	10
30	3140	2075	3	5	12
31	3140	2475	6	12	13
32	3275	475	16	17	18
33	2475	2075	19	20	26
34	2340	1540	21	22	23
35	2740	740	16	24	25

Taking into account the analyzed wind farm, it is found that through the proposed methodology, the wind farm cable route is reduced with 1566 m. In this way, the design cost is also reduced. Regarding these considerations, it should be noted that for large wind farms, which may have long cable lengths (tens of kilometers), the proposed approach proves to be an effective tool in the design process, leading to a minimization of cable route length.

5. Conclusions

The proposed wind farm cable route optimization approach finds all optimal tree configurations with a low computational effort. The ACO metaheuristic algorithm (first step) for the tree configuration allowed the reduction of the search space, making the application of the algorithm possible for large wind farm, with a less computational effort.

In order to optimize the wind farm cable routes, the mathematical model proposed in this paper includes two steps, namely: a first step consists in determining the minimum length complete graph using all wind farm nodes (a single step-up station and all wind turbines); a second step corresponds to a length graph optimization (wind farm topology) resulting optimal from the first step by introducing an arbitrary number of additional nodes (Steiner points).

The cable length of the analyzed wind farm in the study case is reduced with 1965 m. The results of case study demonstrated the feasibility of the proposed method and showed that it can be used as a reliable tool in wind farm design for optimal cable route determination.

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RECONFIGURAREA OPTIMĂ A REȚELEI DE DISTRIBUȚIE A ENERGIEI ELECTRICE DINTR-UN PARC EOLIAN

(Rezumat)

La nivelul rețelelor de transport şi distribuție a energiei electrice sunt esențiale investițiile mai ales din punct de vedere al implementării producerii energiei din surse regenerabile. Topologia unui parc eolian reprezintă de fapt o combinație între sursele de generare (turbine eoliene) şi liniile electrice de legătură între acestea. Ținând seama că pentru un parc eolian liniile electrice de legătură sunt subterane (în cablu), în cadrul lucrării se propune o abordare în două etape pentru optimizarea rețelei de cabluri a parcului eolian. Trebuie menționat faptul că abordarea propusă este compatibilă cu filosofia rețelelor radiale sau ramificare, în vederea optimizării lungimii totale a rețelei de cabluri sau a costurilor cablurilor respective. Noutatea lucrării se bazează pe optimizarea topologiei parcului eolian utilizând o combinație între un algoritm clasic şi unul metaeuristic. Rezultatele studiului de caz demonstrează în mod evident fezabilitatea metodei propuse, putând fi utilizată ca fiind un instrument fiabil pentru proiectarea şi optimizarea topologiei parcurilor eoliene.