

Wind Farm Cable Route Optimization Using a Simple Approach

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Abstract— Worldwide it can be clearly seen that the investment in electricity transmission and distribution infrastructures is very important for the power industry. The wind farm network structure means the combined electric power sources (wind turbine) and branching lines. Also, in a wind farm the branching lines are represented by cable underground power lines (cable). The approach presented in this paper was applied to optimize the electrical inter-array cable systems for wind farms which is compatible with both radial and branched design philosophies, and can optimize for total cable length or cable cost. The newness of the proposed approach is based on a combination of classical and met-heuristic algorithms that use graph theory for wind farm cable route 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 cable route determination.

Keywords - wind farms; power cable; optimization; greedy algorithms.

I. INTRODUCTION

Anywhere in the world it can be clearly seen that the investment in electric energy transmission and distribution infrastructures is very important for the power industry. The “network structure” expression does not have a sufficiently precise definition, referring to “network diagram” or “network configuration”, although its significance is much broader [1]. Generally, network structures represent internal construction that represents nodes and lines.

The wind farm network structure means the combined electric power sources (wind turbine) and branching lines. In a wind farm the branching lines are generally represented by underground power lines (cables). Because wind farm cable route optimization or optimal collector system design (OCSD) is a young field, in [2] a clustering approach is used. Also, for OCSD a mixed-integer programming based formulation has been proposed in [3], [4], [5], a standard genetic algorithm in [6], a hybrid genetic and immune algorithm in [7] and a multi-objective evolutionary strategy is considered in [8]. All of these studies lied to a wind farm layout cost minimization.

It can automatically allocate wind turbines to the nearest stations and obtain the topology structure of cables used to connect wind turbines or 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 [9].

The simple approach presented in the paper was applied in order to optimize the wind farm cable route, being compatible with both radial and branched design philosophies, and can estimate the total cable length or cost optimization. Global optimization of this issue is considered mathematically impossible and the method is adapted to provide a local optimal solution in a useful period of time. In this way, it enables fast estimation of different design configurations while continuous improve the electricity system layout design process [10].

It can automatically allocate wind turbines to the nearest substations and obtain the topology structure of cables used to connect wind turbines or turbine and step-up station. The objective of this optimization is the minimization of the investment costs of cable connection. Then, for the wind farm development, the cable route optimization is a complex stage of the design process. The proposed problem in the paper is the optimal cable topology determination among a various alternatives.

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 of 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 cable route determination.

II. PROBLEM FORMULATION

The proposed problem in this paper is the wind farm optimal topology determination among a various alternatives [11]. This problem is known in literature as a problem of total cost minimization or minimum spanning tree (MST) [12]. A minimalist formulation of the mathematical model for tree networks route optimization problem is the following: by knowing locations of step-up substation and wind turbine in Cartesian coordinates must be determined the cable network route starting from the step-up station (considered first node),

then moving only once at each wind turbine without cycles taking into account the minimum cable route length. On the basis of numerous methods for the synthesis of the optimal networks configuration can be formulated the MST problem (minimum length distribution network). In literature, the MST setting is a typical combinatorial optimization problem, and to solve this there are various deterministic methods [13], [14], [15] or based on artificial intelligence algorithms [16]. 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 the all wind turbine.
- Second step optimizes the length cable route resulting minimum from first step by introducing an arbitrary number of additional nodes.

Below, based on graph theory, the two steps are listed, and for the optimization method the goal function the total minimum length of the wind farm cable route is considered. The newness of the paper consists in the use commonly the ant colony optimization (met-heuristic) algorithm adapted to graph theory for optimal cable route determination and Steiner tree method [17] for reconfiguration of the wind farm cable route.

A. Optimal Network Route Construction Using the Ant Colony Optimization Algorithm

Ant colony optimization (ACO) paradigm is included in relatively recent intelligent agents, based on ant's biological inspiration [18]. 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 (τ_{ik}) , used for the route choosing by the ant from the colony. Initially, the τ_{ik} are 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 (symbolically denoted $L_{\min} = \infty$). The na ants will be distributed as evenly as possible between the graph vertices. In step 2.1 is admitted that the number of vertices and the number of ants is chosen such that $na = m \cdot n$ (m - integer value), while in each node will distribute $m = na/n$ ants. Also, must note that in step 3, Nod_j represents the place where each ant (j) is located at one time.

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.

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1. Initial data:  $n$  – wind turbine;  $na$  – ants;  $(x_i, y_i)$ ,  $i = 1..n$  – Cartesian coordinate;
 $c$  – initial pheromone concentration;  $Q$  – total pheromones quantity of an ant;
 $\rho$  – pheromone evaporation rate;  $T_{max}$  – iteration numbers.
2. General initialization
2.1. Set the ants in the nodes:  $m = na / n$ 
2.2. Set the minimum length route to a very high value:  $L_{min} = \infty$ .
2.3. Set the iteration counter: counter = 1.
2.4. The pheromone concentrations initialization on the edges and distance
computations:
    for  $i = 1$  to  $n$  do
        for  $k = 1$  to  $n$  do
            if  $i \neq k$  then  $\tau_{ik} = c$ 
            if  $i < k$  then
                 $d_{ik} = \text{sqrt}[(x_i - x_k)^2 + (y_i - y_k)^2]$ 
            else if  $i > k$  then
                 $d_{ki} = d_{ik}$ 
3. Select the location nodes for each ant, using a random function:
    for  $j = 1$  to  $na$  do
         $o = (j - 1) \text{ div } m$ ;  $Nod_j = o + 1$ 
4. Insert the first node (current node) in tabu list of each ant:
    for  $j = 1$  to  $na$  do
         $Tabu_j(s) = Nod_j$ 
5. Set the current node position in tabu list:  $s = 1$ .
6. Establish routes (completing tabu lists):
    Repeat
         $s = s + 1$ 
        for  $j = 1$  to  $na$  do
             $i = Nod_j$ ;  $Sum = 0$ 
            for  $k = 1$  to  $n$  do
                if  $k \notin Tabu_j$ , then
                     $Sum = Sum + (\tau_{ik})^\alpha \cdot (1 / d_{ik})^\beta$ 
            for  $k = 1$  to  $n$  do
                if  $k \notin Tabu_j$ , then
                     $P_{ik} = (\tau_{ik})^\alpha \cdot (1 / d_{ik})^\beta / Sum$ 
                else  $P_{ik} = 0$ 
                 $P_{max} = 0$ ;  $k^* = 0$ 
            for  $k = 1$  to  $n$  do
                if  $k \notin Tabu_j$ , then
                    if  $P_{ik} > P_{max}$ , then
                         $P_{max} = P_{ik}$ ;  $k^* = k$ ;
                         $Nod_j = k^*$ ;
                         $Tabu_j(s) = k^*$ 
            Until tabu list is full ( $s = n$ )
7. Total length computation of each ant route:
    for  $j = 1$  to  $na$  do
         $L_k = 0$ 
        for  $p = 1$  to  $s$  do
             $i = Tabu_j(p)$ ;  $k = Tabu_j(p+1)$ ;  $L_k = L_k + d_{ik}$ 
8. Select the minimum length route:
    for  $j = 1$  to  $na$  do
        if  $L_k < L_{min}$  then
             $L_{min} = L_j$ 
9. Update pheromone concentrations on the graph edges:
    for  $k = 1$  to  $NA$  do
        for  $p = 1$  to  $s$  do
             $i = Tabu_j(p)$ ;  $k = Tabu_j(p+1)$ ;
             $\Delta\tau_{ik} = \Delta\tau_{ik} + Q / L_j$ 
        for  $i = 1$  to  $n$  do
            for  $k = 1$  to  $n$  do
                if  $i \neq k$  then
                     $\tau_{ik} = \rho \cdot \tau_{ik} + \Delta\tau_{ik}$ 
10. Stopping criterion:
    10.1 Ending the initial tree calculation: counter =  $T_{max}$ .
    10.2 Empty the tabu lists:
        for  $j = 1$  to  $na$  do
            for  $p = 1$  to  $s+1$  do  $Tabu_j(p) = 0$  and return at five step.
11. Build the minimum tree from obtained trees by each ant. For a ant  $j$ :
    11.1 Find the lowest edge distance from the tree  $T^j$ .
    11.2 If the edge does not already exist, add to the list.
12. The length computation of all obtained edges in the previous step list.
13. Displays the total minimum length tree.
14. End algorithm.

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Figure 1. The ACO pseudo-code adapted for considered approach

Further, the ants should move in different graph nodes, until the tabu lists are complete, each ant making a complete graph tour. In step 6 (Fig. 1), for every ant j , the starting node $i = Nod_j$ and destination node k^* are considered. The k^* should not be included in tabu list, being determined by computing probabilities using the following expressions:

$$P_{ik} = \begin{cases} \frac{(\tau_{ik})^\alpha \cdot (1/d_{ik})^\beta}{\sum_{p \in Tabu_j} (\tau_{ip})^\alpha \cdot (1/d_{ip})^\beta}, & k \notin Tabu_j \\ 0, & k \in Tabu_j \end{cases} \quad (1)$$

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:

$$\tau_{ik} = \rho \cdot \tau_{ik} + \Delta\tau_{ik} \quad (2)$$

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 ($\rho=0.1$), 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 who move from the node i to k , using the equation:

$$\Delta\tau_{ik} = \sum_{j=1}^{na} \Delta\tau_{ik}^j \quad (3)$$

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

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

Stopping criterion (step 10 from Fig.1) 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 [15], [18]: natural; parallel and distributed; cooperative; versatile; robust.

B. Wind Farm Cable Route Reconfiguration using Steiner Method

In the literature, the minimum network length determining through 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 [1], [17]. 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 the 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 represent the initial number nodes and l is the additional number nodes. Thus, for the minimum wind farm cable route length search the mathematical methods based on analyzed variables number reduction are used [15].

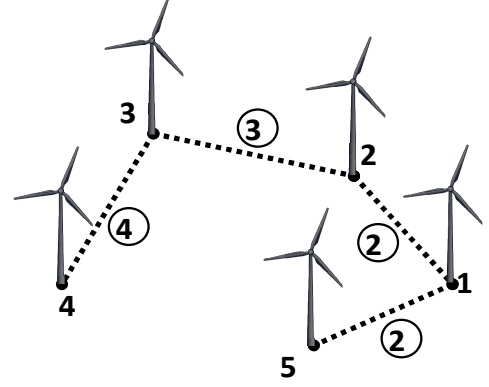


Figure 2. Example of a minimum length of a wind farm cable route

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.

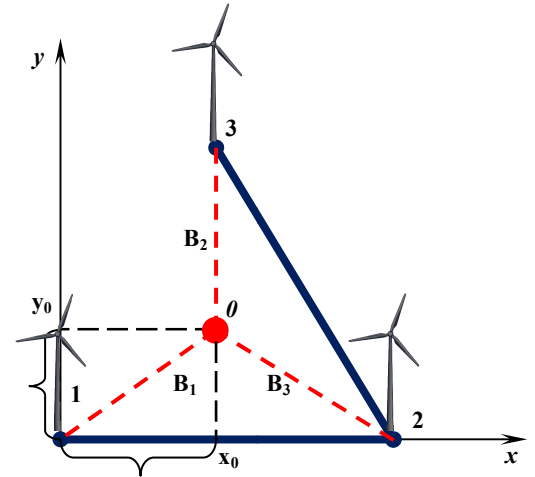


Figure 3. Wind farm cable route reconfiguration using Steiner points (0)

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 least three nodes and one Steiner point. Hereinafter the Steiner tree construction using the so-called Euclidean constructions is presented in Fig. 4.

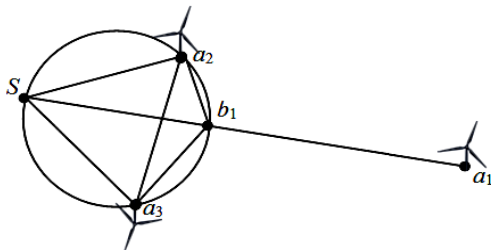


Figure 4. Euclidian construction of the Steiner tree

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:

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

III. A SIMPLE APPROACH FOR WIND FARM CABLE ROUTE OPTIMIZATION

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.

developed. The application uses a combination of ACO and Steiner algorithms and the goal function is minimum cable route length (between wind turbines and the step-up station) with radial structure restrictions.

- Input data: general data (step-up station and all wind turbines); consumers data (Cartesian coordinates, wind turbine name); the step-up station is always 1.
- Determining the minimum cable route length with ACO algorithm (minimum length of the wind farm configuration).
- 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.
- 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.

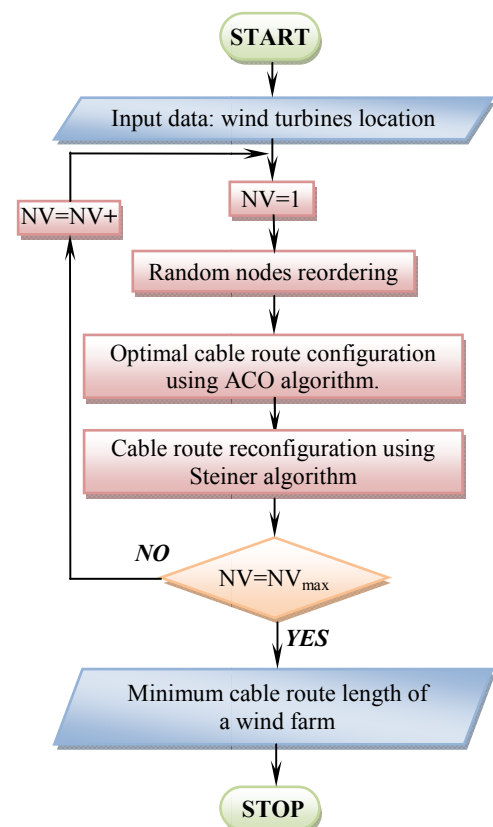


Figure 5. A simple algorithm for wind farm cable route optimization

To highlight the utility of the simple approach proposed in the paper, for optimal cable route determination, a wind farm with 25 wind turbine was analyzed. In this context, input data of test wind farm distribution with 26 nodes (one step-up station and 25 wind turbine) is presented in Fig. 6 [4].

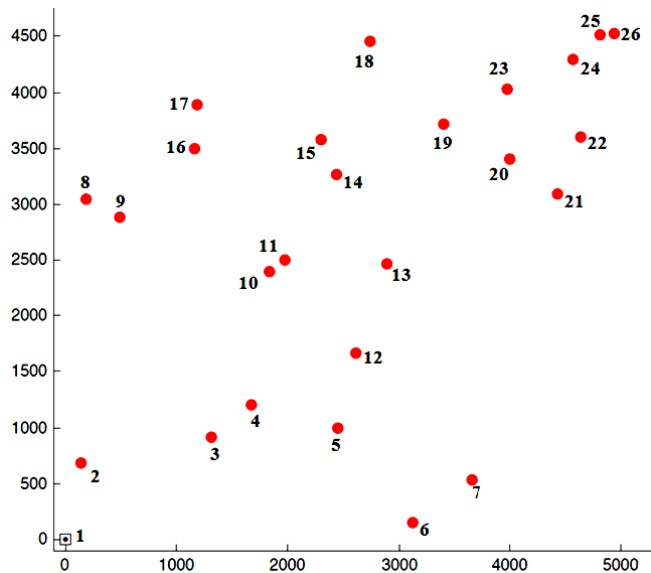


Figure 6. The positioning of wind turbine in the analysed wind farm

In first step, based on methodology aforementioned, using a successive search technique (ACO) the wind farm cable route length results 16618 m, being the configuration presented in Fig. 7 [4]. By optimizing minimum graph length obtained using ACO, in a second step, to allow new route construction, are needed four additional Steiner points, and the minimum wind farm cable route length resulted is of 14653 km.

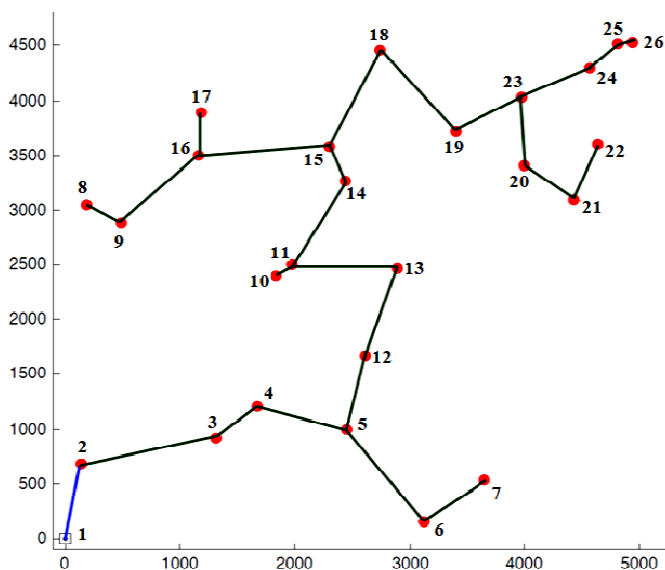


Figure 7. Wind farm cable route optimization using ACO algorithm.

TABLE I. ADDITIONAL BRANCH POINTS (STEINER POINTS) NECESSARY IN THE ANALYSED WIND FARM

Number of Steiner points	Steiner point Cartesian coordinates		Nodes which form the Steiner point		
	X [m]	Y [m]			
27	2260	1290	4	5	12
28	1525	3640	15	16	17
29	2790	3905	15	18	19
30	4360	3375	20	21	22

The additional Steiner points are summarized in Table I such as: additional node number, the Cartesian coordinates and the three nodes which could form the Steiner branch point.

Taking into account the analyzed wind farm it is found that through the proposed methodology usage, the cable route of the analyzed wind farm is reduced with 1965 m. In this way the design cost are also reduced. Regarding these considerations, it should be noted that for large wind farm, 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.

V. CONCLUSIONS

The proposed wind farm cable route optimization approach showed to be capable of finding all optimal tree configurations with a low computational effort. The use of a met-heuristic 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 turbine);
- a second step corresponds to a length graph optimization (wind farm cable route) 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 clearly 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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