Electrical Cable Routing Optimization in Offshore Wind Farms

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Abstract. Wind energy has garnered increasing attention as a leading source of renewable energy, thanks to its widespread availability and increasingly competitive costs. This manuscript proposes a model for optimizing the routing of electrical cables and the interconnection of system components in previously defined positions — namely, wind turbines and the electrical substation — with the objective of automating the design of offshore wind farms layout. The wind farm electrical cable routing problem must consider design and seabed constraints, while coordinating different objectives, such as minimizing cable length, enhancing energy efficiency, and reducing overall costs. Specifically, the developed routing model aims to minimize the total length of electrical cables, using a minimum spanning tree (MST) approach. In the model, wind farm elements are modeled as a graph, with turbines and substations represented by nodes and possible interconnections between elements represented by the edges. A case study was conducted to assess the proposed model, and the results demonstrate the feasibility of the tool. With the proposed tool, we expect to reduce the time required for designing offshore wind farm projects, while also delivering more efficient and cost-effective solutions.

Keywords: Wind energy, offshore wind farms layout, routing of electrical cables.

1 Introduction

Offshore wind energy generation plays a vital role in achieving the objectives of the global energy transition, particularly due to its high-power generation potential. In this context, optimizing the design and operational efficiency of offshore wind farms has emerged as a key research priority.

One of the key components in the design of an offshore wind farm is the electrical collection system, which connects wind turbines to substations and ultimately to the onshore power grid. The configuration of this cable network has a significant impact on both the capital and operational expenditure of the project. The design of an offshore wind farm involves, among other aspects, determining the placement of wind turbines and defining the layout of the electrical cables that connect these turbines to transformers and the power export infrastructure. To reduce project costs, the total length of electrical cables must be minimized.

The optimization of offshore wind farm design, particularly concerning the layout of turbines and the configuration of the electrical collection system, has been studied in recent years. Offshore wind farm cable layout design problem is often modeled as a variation of classic combinatorial problems. For instance, Gonzalez-Longatt [1], Bauer and Lysgaard [2] and Srikakulapu and Urundady [3] formulated this problem as variations of the traveling salesman problem. To achieve solution, authors proposed different methods, comprehending genetic algorithm [1], Clarke and Wright savings method [2], or an elitist ant colony optimization algorithm [3]. Beyond combinatorial formulations, several researchers employ metaheuristic algorithms specifically for electrical network optimization. For instance, Marliere et al. [4] proposed a bat algorithm, a nature-inspired metaheuristic, to solve formulations for the wind farm cable layout design problem. An advanced formulation of the problem, incorporating both cable routing and cable sizing, was proposed by Pillai et al. [5]. In their methodology, cable paths are determined using a heuristic approach. Cable type selection is modeled as a Capacitated Minimum Spanning Tree problem, which is then solved using a commercial Mixed-Integer Linear Programming solver.

In this context, the main objective of this manuscript is to propose a mathematical model inspired by the Minimum Spanning Tree (MST) for the design of electrical cable layouts in offshore wind farms—specifically, to determine the routing of power lines connecting turbines and transformers. As the main innovation, the proposed model considers constraints related to underwater obstacles and ocean bathymetry.

The rest of the manuscript can be described as follows. In Section 2 we present the panorama of wind energy in the world and specifically in Brazil. Section 3 describes our methodology, with our proposed model and solution approach. To test our approach, we conducted a case study presented in Section 4 . Finally, in Section 5 the final conclusions and the future works proposals are described.

2 Wind Energy

Wind power generation has increasingly stood out within the scope of renewable energy worldwide, mainly due to the availability of wind resources and increasingly competitive infrastructure costs.

In Brazil, wind energy is the second largest source in the country's energy matrix, second only to hydroelectric power. In this scenario, the country reached a milestone of 93.1% of electricity generation from renewable sources in 2023 [6], with wind power registering significant growth in recent years. This growth can be largely attributed to global incentives aimed at promoting the use of clean and sustainable energy sources.

In the offshore context, wind power installed at sea grew by 24% globally in 2023 compared to the previous year, bringing total global offshore wind capacity to 75 GW [7]. Although Brazil does not yet generate offshore wind energy, the country's potential in this area is internationally recognized.

As mentioned above, the potential for wind energy production has grown substantially. For the installation of new wind farms, particularly offshore, it is necessary to evaluate hundreds or even thousands of design alternatives. To prevent suboptimal use of wind turbines within the licensed area, turbines must be positioned to maximize energy generation, while the connection matrix should be designed to minimize the total length of electrical cables.

3 Methodology

In this study the scenario is modeled by a graph. Nodes are positioned at the locations of the turbines and substations, while edges are created connecting the different nodes to each other. This approach creates a large number of edges that need to be examined; therefore, it is important to first simplify the graph by removing edges that are unnecessary or unfeasible. Two filtering conditions are used to cull a significant number of edges. Firstly, any edge that overlaps another node is removed as redundant, since there are already edges that connect to the third node and the nodes of the examined edge. Secondly, if the edge crosses a subsea obstacle the edge is also removed since it is not possible to install a cable connecting those nodes. Finally, the weight of any remaining edges is calculated using the distance between nodes and the bathymetric information using a 10-segment discretization of the route to determine the 3D length of the cable.

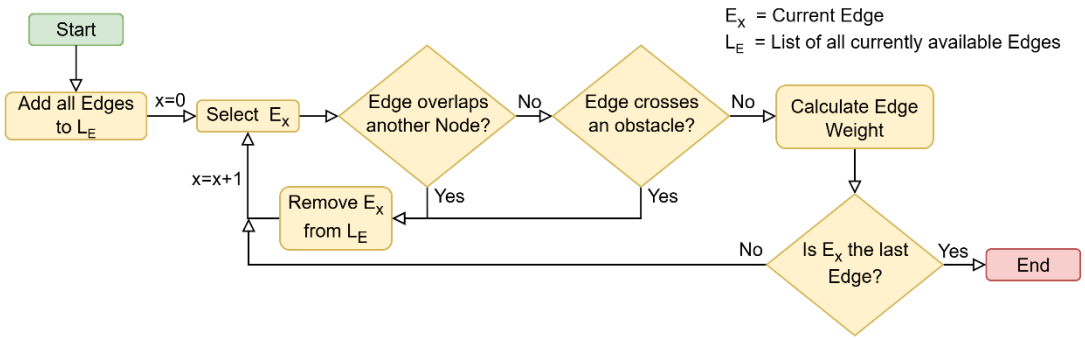


Figure 1. Flowchart of Edge Removal Algorithm

Now that the list of edges has been reduced, the algorithm can create the cable network connecting the turbines to the substations. The Prim's algorithm [8], a greedy method for finding a minimum spanning tree in a weighted, connected graph, was used to determine the optimal set of connections. Starting at each substation node at the same time the algorithm finds the edge with the lowest weight and adds all edges that connect to its node to the list of currently available nodes, it then selects the next lowest weight node, and the process repeats until the entire graph has been evaluated. After the complete graph is analyzed the tree of each substation is separated based on the branches that start on each substation. This method ensures that the total length of cables is minimized.

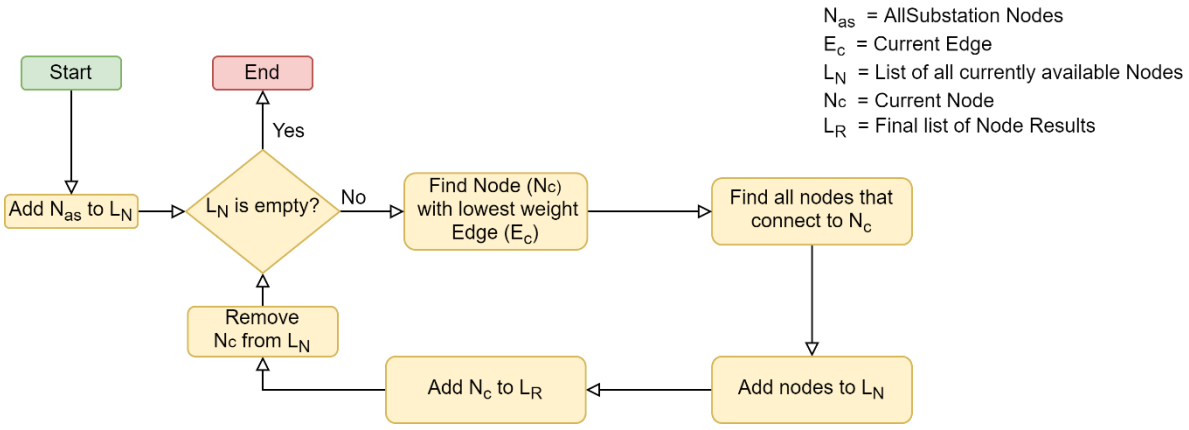


Figure 2. Prim's Algorithm Flowchart

4 Case Study

For this study, data from one of the world's largest operational offshore wind farms, the London Array, was used. Located 20 km off the coast of Essex, United Kingdom, this wind farm comprises 175 turbines with a total installed capacity of approximately 630 MW. Its layout was adopted as the baseline for evaluating the proposed methodology, as it reflects the complexity of a real-world system, especially in terms of number of turbines. The case study explores three scenarios, each one with a different number of substations. The initial scenario, represented in Figure 3 (a), has fictional bathymetry data derived from real world conditions to simulate an offshore environment shown in light blue, the turbines are placed as green circles and there are two geological faults present in the area represented as black lines that prevent cable installation across them. The bathymetry is used to compute the three-dimensional length of the cables and the geological faults affect the feasibility of certain edges. Therefore, these datasets have a decisive impact on the results.

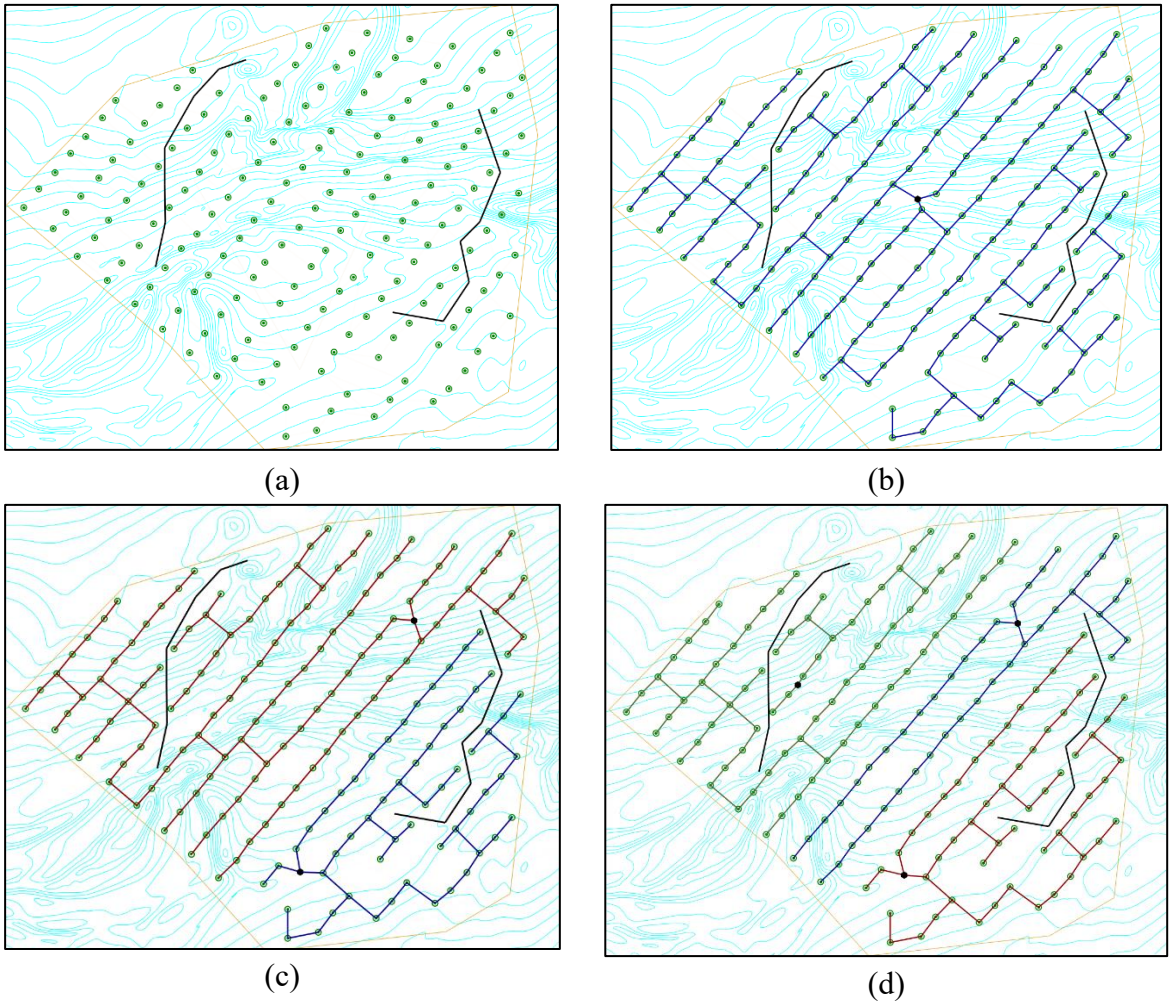


Figure 3. Scenarios: (a) Initial Scenario, (b) One Substation, (c) Two Substations, (d) Three Substations

All scenarios share the same number of turbines (175), fixed in theoretical positions, inspired by the positions of the original London Array wind farm, throughout the study. Each turbine and substation were limited to a maximum of three "upstream" connections. The connections are all made in a radial topology with no restrictions whatsoever in terms of number of turbines in each path branching from substations. The results are show in Figure 3 (b), (c) and (d), where substations are represented by black hexagons and each substation branch is highlighted in a distinct color for clarity.

The first scenario includes a single substation positioned at the geometric center of the defined area. The second scenario has two substations located in the same relative position as the original London Array wind farm.

Finally, the third scenario features three substations arranged to form a triangular configuration within the study area. Each scenario has a distinct level of complexity, as increasing the number of substations expands the range of possible connections —thereby increasing the number of edges to be evaluated by the proposed methodology. Table 1 presents the total number of possible connections in each scenario, as well as the reduced number of possible connections obtained after the first step of the methodology, which consists of edge simplification.

Table 1. Scenario Data

Scenario	Number of Substations	Number of possible connections	Number of possible connections after simplification	Total Length of Electrical Cable (km)	Number of Turbines per Substation
A	1	15400	3668	120.6	175
B	2	15575	3689	119.9	118 / 57
C	3	15750	3704	119.0	75 / 57 / 43

The edge simplification is an important step to the proposed methodology, as it reduces significantly the number of edges to be evaluated, thereby improving computational efficiency. In scenario A, the number of edges was reduced by 76.2%; in scenario B, by 76.3%; and in scenario C, by 76.4%.

The computational time required to solve each scenario was also assessed. Each scenario was executed five times, and the average time was recorded. The results show that scenario A took 147.3 milliseconds, scenario B 146.2 milliseconds, and scenario C 166.4 milliseconds. As expected, the processing time is minimal with minor fluctuations related to the number of edges that must be evaluated during the optimization process and current processor workload. It is worth noting that all executions within each scenario produced identical results, as expected, since the proposed methodology follows a deterministic approach. The results show that the algorithm is capable of defining a cable network that minimizes the total cable length while connecting to the required substations and avoiding the subsea obstacles present in the seabed, using minimal computational time.

5 Conclusions

The main objective of this paper was to optimize the routing of electrical cables of an offshore wind farm by minimizing the total cable length from wind turbines to energy substation, while controlling the maximum connections per node and considering seabed bathymetry and obstacles. In addition, a computational tool was also developed to automate the layout design of offshore wind farms. To achieve these objectives, the scenario was modeled by a graph where turbines and substations were represented as nodes and electrical cables as edges connecting different nodes. The first step of the method was to reduce the large number of possible edges by removing those that overlapped with another node or crossed a subsea obstacle. Following this, Prim's deterministic algorithm was applied to generate the tree connections of the graph. To evaluate the efficiency of the proposed method, a representative real-world case study was processed considering scenarios with one, two and three substations. The results show that the algorithm can automatically provide efficient electrical cable routing, minimizing the total cable length, considering different number of substations and avoiding the subsea obstacles with minimal computational cost.

The positions of the wind turbines and the energy substation were taken as fixed, as well as the number of substations required for each scenario. In this way, it is possible to suggest, as future work, the inclusion of more variables to be optimized. Such as, substation position which can consider seabed topological characteristics; the number of substations since in large wind farms the installation of multiple substations can be more efficient from both technical and economic aspects; the cable section dimension, as the transmitted power varies throughout the network and it may be necessary to adapt the cable diameter to reduce electrical losses; the distribution of the connection of turbines to substations, so as to more evenly allocate the energy load; and last but not least, the position of wind turbines can be optimized to mitigate the wake effect, maximizing energy production and, simultaneously, reducing cabling costs. These proposals aim to make the optimization model even more realistic and applicable to the planning of commercial offshore wind farm projects contributing to increasing energy efficiency and reducing the costs of the entire system.

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