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TECHNICO-ECONOMIC OPTIMAL CABLE LAYOUTS FOR OFFSHORE WIND FARMS

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Abstract

Renewable energy sources are more than ever in the focus of research, funding initiatives and governmental policies. At the heart of this debate is the desire to make such sources cheaper, cleaner and more efficient. Wind generation, in particular, presents a potential that tends to be increasingly exploited and may open the way for the application of new technologies, such as superconductors. In this context, it is pivotal to assess the impact of these innovations. The present study focuses on a fundamental aspect of the design of offshore wind farms: the cabling layout. With new innovations, the main motivation is usually an economic one, to reduce costs. Represented by the Levelized Cost of Energy (LCOE), this study attempts to contribute to an LCOE minimization by proposing a general method that optimizes a cabling layout while maintaining appropriate computational times. This method is, in turn, coupled with a general LCOE minimization algorithm that will be part of another study. The thesis will firstly present a literature review of the most relevant research conducted in this field and will detail the existing gaps that exist. After this, the proposed method of this study is presented in a step-by-stem manner and applied to a real-life wind farm which is currently under construction (Saint-Brieuc wind farm). An assessment of the cable losses is conducted later on in the power flow section. Finally, a discussion will be conducted and divided into three parts: a comparison of the proposed method with the existing literature, a comparison between the real-life cabling design at St. Brieuc and the method proposed here, and a comparison between the different types of algorithms that could have been used in the proposed solution.

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Introduction

The renewable sources of energy are expected to become responsible by one-third of the electricity production worldwide, overpassing the coal leadership, by 2025 [1]. While hydropower will still be the most representative renewable source, wind energy is projected to experience a massive growth in the coming years. From 2019 to 2025, the global wind capacity is expected to almost double, reaching 1.1 TW. Onshore generation, accounts for 95% of the total wind capacity in 2019. However, the offshore technologies should experience a significant growth, reaching 8% of the wind generation capacity by 2025.

In this context, decreasing costs is always a concern. In the energy production industry, the levelized cost of energy (LCOE) is the main indicator for representing the cost of an installation and to determine the economic viability of a certain technology. In this respect, the main interest is, without no doubt, to minimize this indicator. For offshore wind energy, the LCOE depends on many factors such as the capacity factor, the wake effect and other losses, and the various costs, divided into the capital expenditure (CAPEX) and the operating expenditure (OPEX). In recent years, offshore wind energy LCOE has experienced a sharp decrease thanks to innovations that have arisen in this industry. The projections for the coming decades are that this decrease will continue as stated in the GPRA 2030 target (Figure 1) [2].

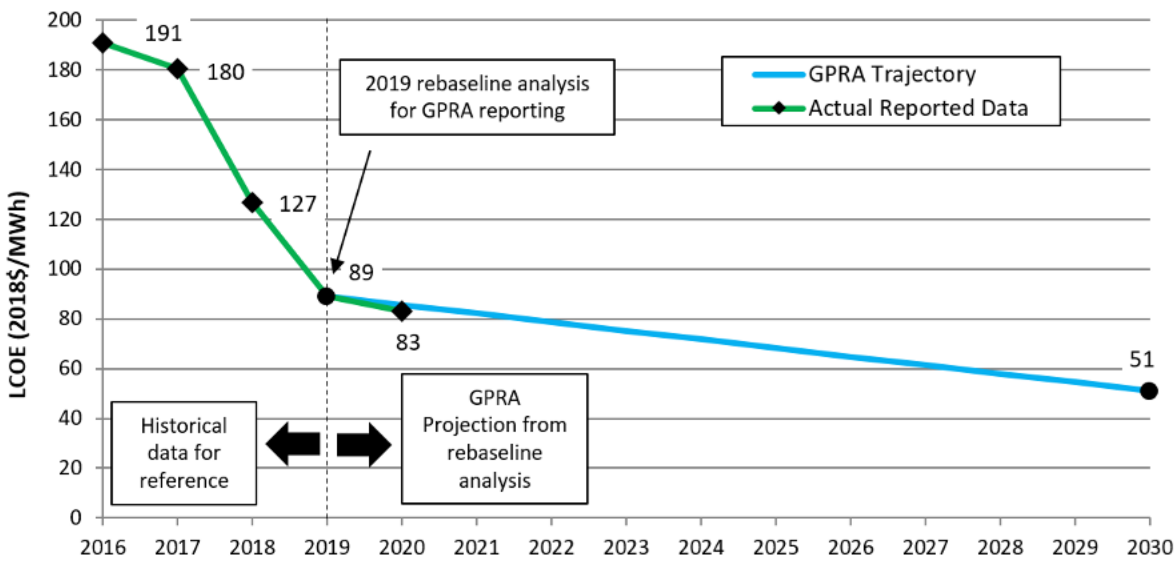
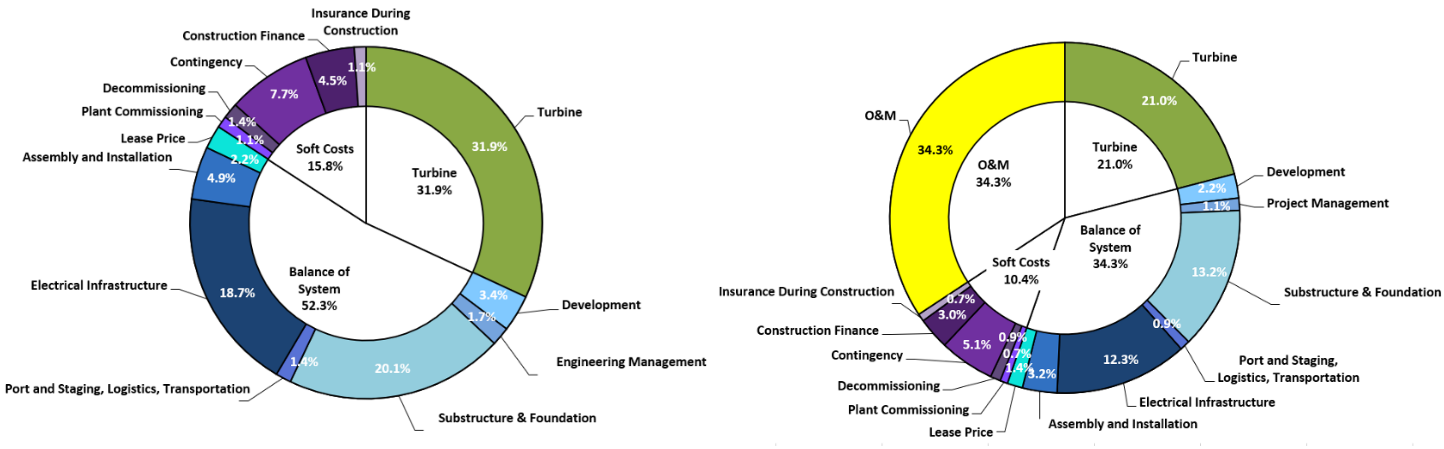


Figure 1 - Historical and projected LCOE of offshore wind energy. Source [2]

If we now take a look at a detailed decomposition of the costs obtained from [2], Figure 2.b represents the average LCOE cost distribution of a reference fixed-bottom offshore wind farm. The electrical infrastructure accounts for 12.3% of the total costs. If we now take a closer look at the CAPEX costs distribution in Figure 2.a, this cost accounts for 18.7%.



(a) CAPEX decomposition (b) LCOE decomposition

Figure 2 - Costs of a reference fixed-bottom offshore wind farm. Source [2]

Electrical Infrastructure

In Figure 3 the electrical infrastructure of an offshore wind farm is presented. Offshore wind farms consist of arrays of turbines linked together in a given layout. The energy generated by the turbines is directed through distribution cables through the inter-array cabling. It is usually at medium-voltage alternating-current (MVAC), at 33 kV or 66kV. From the collection point, known as the offshore substation, the energy gets transmitted to the grid via a cable at high-voltage alternating-current (HVAC) linking the offshore substation and the onshore substation

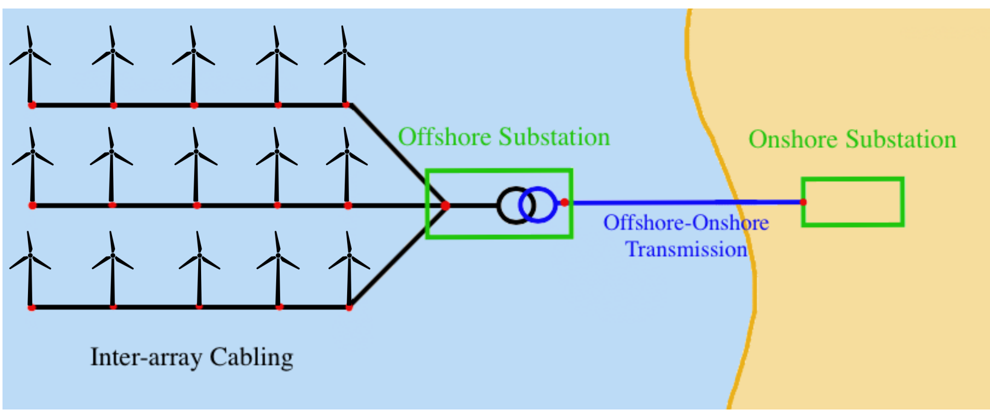


Figure 3. Electrical infrastructure of an offshore wind farm. Source: Author

For the power transmission system, different technologies can be used: high-voltage alternating-current (HVAC), medium-voltage alternating-current (MVAC), or systems using direct-current (DC) instead of AC. [3]

Since the development of transformers, which allow for high power and insulation levels, have overall lower loses, and relatively simple operation and maintenance, HVAC has been the dominant technology for electricity transmission all over the world. Regarding offshore wind farms, it was indeed the main technology in the early years of development, when wind parks had a small rated capacity and were built close to shore. Nevertheless, nowadays, the offshore wind farm characteristics determine whether HVAC is the optimal option. [3]

The basic functioning of an HVAC transmission is the following: the power produced by the wind farm at MVAC is sent to an offshore substation, which contains a power transformer, which steps up the voltage to values typically between 110kV and 275kV. The power is transmitted at this voltage through subsea cables, generally buried until it finally reaches the onshore substation, where the connection to the grid is made. Other components, such as switchgears and reactive power compensation systems are necessary to guarantee the power transmission. [3]

As a visual example, Figure 4 represents a cabling layout design of the Thanet wind farm. The motivation of this study is therefore to take a closer look at the electrical infrastructure. We will analyze and propose a method that will minimize the cabling costs and therefore contribute to the decrease of the LCOE.

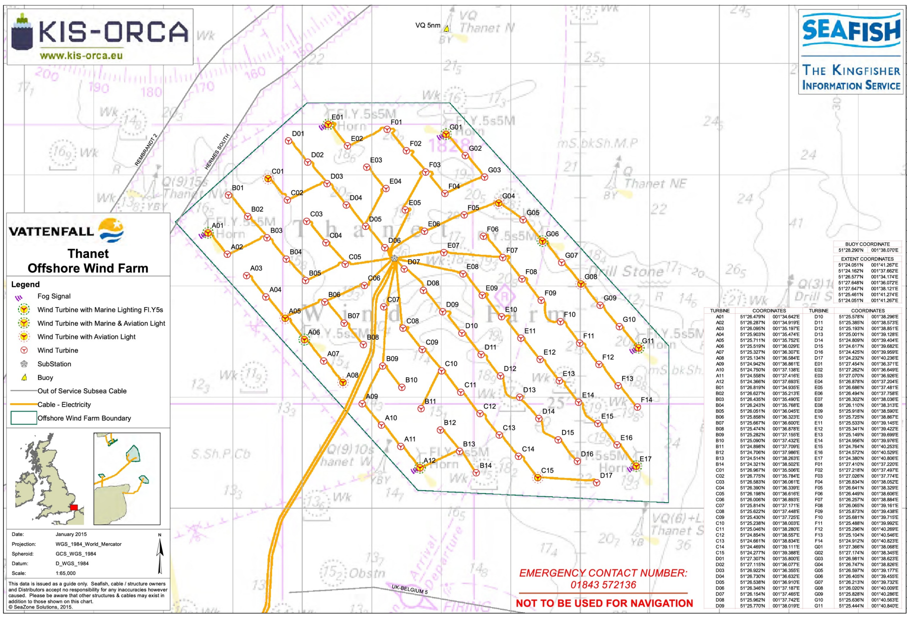


Figure 4 - Example of a real-life offshore wind farm cable layout. Thanet wind farm, UK. Source [4]

This thesis is organized as follows. A review literature review will be conducted in the first part of the study, analyzing the main methods used and pointing out the possible research gaps that exist. In Chapter 2, this study's proposed method of cable routing is detailed and will be applied to the Saint-Brieuc wind farm which is currently under construction. Finally, in Chapter 3 a discussion will take place by comparing the solution proposed in Chapter 2 to the main literature methods and to the real-life solution being constructed at St. Brieuc.

Chapter 1
Literature Review

1.1. Introduction

In this chapter, a review of the different cabling design methods is undertaken. We will present the main methods used nowadays and attempt to extract the advantages and disadvantages of each one.

Research on this subject is relatively recent, dating back to 15 years. Over more, the fact that the studies have been conducted by scientists of many disciplines explains the reason for which a wide variety of methods and mathematical formulations exist. This fact makes it ever more important for a comprehensive review of the existing scientific literature. The most notable reviews in this sense are Lumbreras et al. (2012) [5], Pérez-Rúa et al. (2019) [6] and Hou et al. (2019) [7].

As very complete literature reviews in this field have been published in recent years, notably [6] and [7], the present chapter will be a summary of a past literature reviews, while incorporating other recent studies not mentioned in the former, and modifying the vocabulary used in these reviews.

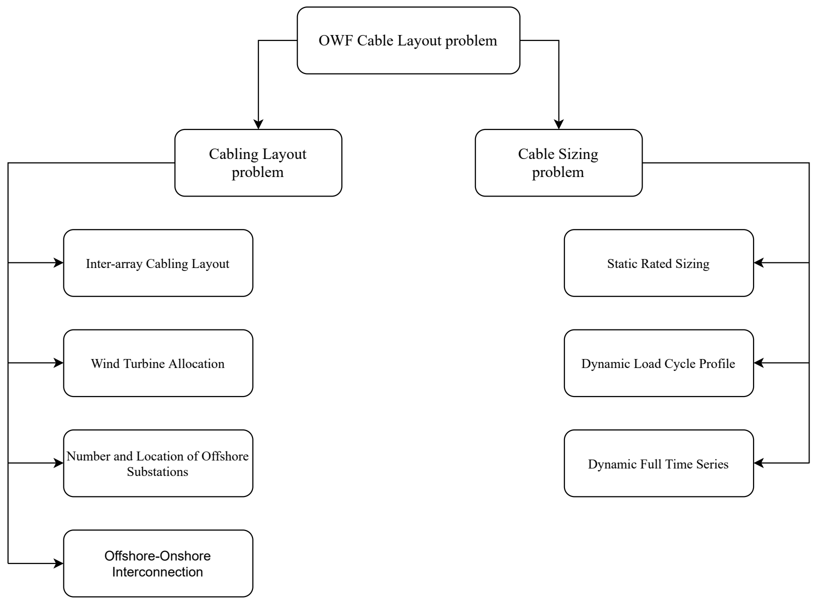


Figure 5 - Main study fields of the Offshore Wind Farm (OWF) Cable Layout problem.
Source: Author

The offshore wind farm cable layout problem can be divided into two subproblems, as can be seen in both branches of Figure 5 and, as such, this chapter will be divided in to the following sections: firstly, the Cabling Layout problem consists in four subproblems represented in the lefts branch of Figure 5. These four subproblems study the inter-array cabling layout; the partitioning of the wind farm; the number and location of the offshore substations; and the interconnection of the offshore cabling to the onshore grid. Secondly, the Cable Sizing problem is a classification problem with three main techniques: static rated sizing, dynamic load cycle profile and dynamic full time series.

1.2. Cabling Layout problem

In this section, the problem of the optimal cable layout (without sizing) is detailed. This problem can be divided into four subproblems, as shown in the right branch of Figure 5. These subproblems are of increasing complexity where in each next step, new constraints are considered.

1. Inter-array cabling layout problem: here, the best cable configuration is searched. It is a graph problem where variations of the MST algorithm are usually used and different topologies can be chosen (radial, radial plus star, loops). In this section, it is assumed that there is a single offshore substation.

2. Wind Turbine allocation problem: this part considers a case where the number of possible offshore substations is larger than one, while considering the number and location of the offshore substations predefined. It therefore undertakes the partitioning of the wind farm.

3. Number and location of offshore substations: this problem determines the optimal number of offshore substations, that is, how many clusters should the wind farm optimally have. Once this is determined, the optimal location for each one is assigned.

4. Offshore-onshore interconnection: this final part analyses the connection from the medium voltage (MV) inter-array cabling to the high voltage (HV) onshore grid.

We will now take a deeper look into these four subproblems and the different methods that are used in the literature to solve each one of them.

1.2.1. Inter-array cabling layout problem

This problem can be formulated as a minimum spanning tree (MST) which would obtain a cable configuration representing the connections between wind turbines and between the offshore substation. The Capacitated MST (CMST) would be a more appropriate formulation of this problem, as it adds constraints in the form of a weight assigned to each edge. These two problems are both NP-hard [8] and can be easily formulated and implemented. Other possible formulations can be found in other fields such as the telecommunication network designs, or network planning. However, if additional constraints need to be introduced, such as spatial constraints (obstacles on seabed, seabed bathymetry) or the non-crossing of cables, new formulations that are specifically designed for this problem should be applied.

Two choices have to be made that vary between different studies of the literature:

- Topology: radial, radial plus star, single looped or other. The topology determines the structure the cable layout is going to have. Factors such as cable reliability or costs influence the decision between one topology or another. A notable study comparing different topologies is Bahirat et al. [9]

- Objective: cable length, cost, cost plus reliability, cost plus losses or cost plus reliability plus losses. This choice determines the optimization target to be minimized.

The different methods used to solve the inter-array cabling problem can be identified as clustering methods, heuristic, metaheuristic or global optimization techniques. Clustering methods divide the wind farm into smaller groups of wind turbines by maximizing the resemblance of each cluster; the most popular algorithms are the K-means, the Fuzzy C-means (FCM) (both unsupervised machine learning algorithms) [10].

If we now pass on to heuristic methods, we can find algorithms such as Dijkstra, Prim, Kruskal, etc. which attempt to solve the MST problem. The algorithms are usually deterministic. Studies such as [11] have used Dijkstra, other studies use Prim [12], and others modify MST algorithms by incorporating Steiner points [13] or by predefining a mesh [13]. Heuristics can be combined with clustering techniques in order to avoid the limitations that usually appear in simple heuristic methods, such as coping with cable capacities.

Metaheuristics are an enhancement of heuristic methods that use probabilistic criteria in order to search the whole problem space, and therefore avoid local minima [14]. The most used methods found in the literature are: Genetic Algorithms (GA) [15], Particle Swarm Optimization (PSO) [16], Simulated Annealing (SA) [17], and Ant Colony Optimization (ACO), Ant Colony System (ACS) [18].

Lastly, global optimization methods are also present and different formulations exist: Binary Integer Programming (BIP), Mixed Integer Linear Programming (MILP) ([4] [19] [13]), Mixed Integer Quadratic Programming (MIQP) and Mixed Integer Non-Linear Programming (MINLP). These global optimization methods usually use external black-box solvers.

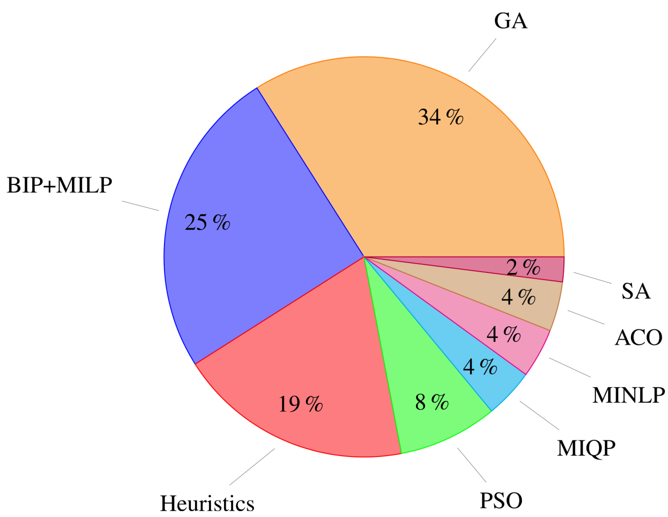


Figure 6 - Distribution of applied methods in the scientific literature. Source [6]

Figure 6 can give a visual representation of the most used methods to solve the offshore wind farm cable configuration problem. This chart confirms that there exists no clear consensus for a specific method and many different techniques are being used to attempt to solve this problem.

1.2.1.1.Considering Bathymetry

The bathymetry of an area refers to the set of data detailing seabed depth and the surface’s morphology, as shown in Figure 7. During the inter-array cabling problem, most studies consider 2-dimension models of a wind farm. However, the depth and surface of the seabed should not be neglected, especially when dealing with such elevated cable costs [20]. According to Nielsen (2003) [21], foundation costs increase 2% per added meter of depth.

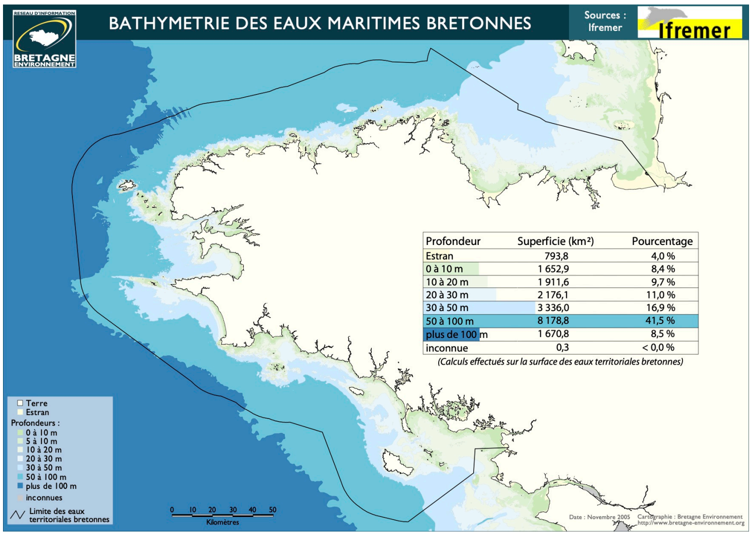


Figure 7 - Example of bathymetric data of the coast of Brittany

Some studies such as [22] [23] have considered bathymetric data to determine the feasibility of wind farm locations, especially analyzing the type of foundation that are used. Dutta et al. [11] conducted a study where the seabed was considered in order to restrict certain areas of a wind farm when designing the cable layout. However, during this review, it has been evident that very few studies incorporate bathymetry for the offshore cable layout problem and its costs, apart from the aforementioned.

1.2.2. Wind turbine allocation problem

In this section the assumption of considering more than one offshore substation is undertaken. However, the number and locations of the offshore substations are assumed to be predefined, and their determination will be discussed in Section 1.2.3.

This problem therefore increases in complexity as compared to the previous section and, as seen in the literature, there exist three main methods:

(a) A single step approach, by simultaneously solving this problem together with the one described in Section 1.2.1. In this approach, mathematical formulations can be used, and the optimization process deals with the full problem ([4] [24]). However, even though this method is the exact way to solve the problem, in the case of large wind farms, this technique is usually computationally expensive.

(b) A multi-step approach, where the wind turbines are firstly clustered and then each cluster is independently solved as formulated in Section 1.2.1. This method helps to manage the complexity of the problem, by dividing and solving a series of subproblems. For the initial clustering subproblem, two possible methods are used: i) mathematically formulating the problem using network theory, or ii) directly apply clustering algorithms such as K-means, QT or FCM.

(c) A nested approach, where there is an outer loop that deals with the wind turbine allocation problem, and an inner loop that tackles the cable layout problem. In this iterative approach, the wind turbine clusters can be updated based on the calculations of the cable path problem, where cheaper solutions are iteratively searched for.

There exist a wide variety of algorithms that deal with the clustering problem, such as the K-means family, the C-means algorithms, etc. From the K-means algorithms, we can distinguish the traditional kmeans algorithm, the kmeans++ and the new Constrained Capacitated K-means++ (CC-kmeans++). This family of algorithms is of NP-hard complexity. A benchmark comparison was made in [13] and, as expected, kmeans++ performs better than kmeans. However, according to this study, there exists a tradeoff when considering CC-kmeans and kmeans++: the latter is faster while the former outputs a better optimum, although only marginally.

1.2.3. Number and location of offshore substations problem

In this section the number and location of offshore substations aren't predefined. This is yet another step up in the complexity of the problem and can therefore be regarded as a variant of the problem of Section 1.2.2. There exist three different types to this problem:

- Variable number and variable location of offshore substations. In this case, many methods use a multi-step approach such as [25] (MILP), [26] (GA), [27] (FCM plus Prim algorithm). In [27] an FCM algorithm was used to cluster wind turbines into the offshore substations and the locations were determined by obtaining the centroids of each cluster geometry.

- Fixed number and variable location of offshore substations. This is usually implemented in single step approaches using mathematical formulations such as in [28]. Another possibility is to consider a multi-step approach, such as in Pillai et al. [13] where a Capacitated Centered Clustering Problem (CCCP) and a heuristic is used to find the substation locations. Nested approaches are also used, such as in Shin et al. [29].

- Variable number and fixed location of offshore substations. This formulation is rarely used and can be found in Lingling et al. [30].

1.2.4. Offshore-Onshore Interconnection problem

In this section, two distinct situations can be considered:

(a) Link between few offshore substations and one onshore connection point (OCP)

(b) Link between multiple offshore substations and multiple OCPs.

In the first case, many studies consider that the offshore substation locations (in a given range) does not influence the transmission costs. However, when considered, such as in [16] [28] [30] [31], there exists a tradeoff between the inter-array cabling cost and the interconnection cost: as the length of the link OSS-OCP decreases, so will the transmission cost decrease while the inter-array cabling cost could increase. Castro-Mora et al. [31] analyses this tradeoff.

In the more general second case, with multiple offshore substations and OCPs, the studies usually disconsider the inter-array cable design and calculate instead the total installed power of the offshore windfarm. In Ergun et al. [32] a GA has been implemented which provides a ranking by sorting the total lifetime costs of the wind farm for different options to interconnect offshore windfarms between each other and to OCPs.

1.3. Optimal Cable Sizing

This section describes the problem of optimally assigning the appropriate cables to each cabling section. To do so, the nominal current of each section is usually studied. In most of the scientific literature, the value of this current can be assumed smaller than its nominal value due to the high variability that characterizes offshore wind power, and its low capacity factor [33].

As can be seen in the right branch of Figure 5, there exist three main techniques for this classification problem: static rated sizing, dynamic load cycle profile and dynamic full time series.

1.3.1. Static rated sizing

This method is the recommended industry standard, and a more detailed explanation can be found in various IEC technical documents [34] [35]. It a straightforward method which consists is considering the nominal current with a 100% capacity factor. The smallest cable supporting an equal or greater nominal current is selected.

This standard method therefore considers static conditions at rated power for a given wind farm.

1.3.2. Dynamic load cycle profile

This is a conservative method that consists in finding the worst-case dynamic load profiles through a specific time period, as detailed in [36]. It takes into account the variability of production of energy and consists in statistically analyzing the historical wind data in different time-steps which vary in duration (such as 7, 10, 40 and 365 days, as recommended in [37]), in order to get a global analysis (in 365 day time-steps) and more detailed views (in 7 or 10 day time-steps) of the windiest periods. From these different time-steps, the RMS current value is calculated over the whole time period available in the historical wind data, which allows to identify the windiest years to analyze. Now, these years, which are considered to be the worst-case scenarios, are analyzed one by one to obtain the most conservative estimate of a maximal power production. Once this is obtained, the cables are sized similar to the previous method: the smallest cable supporting an equal or greater nominal current is selected.

A recent article published by the SATIE lab [38], presents the dynamic rating method applied to wave energy test sites in order to validate and later on apply this technique to larger scale wind farms.

1.3.3. Dynamic full time series

This final method, unlike the two previous ones, considers the reliability of a wind farm. The technique uses a full and high-resolution time series to perform an electrothermal analysis. To conduct the reliability analysis, extra information is required such as generated power, seabed surface temperature, thermal parameters, etc. Different solving methods have been used: Step response, Final element method or Thermo-electrical equivalent model [39].

1.4. Summary

This chapter has presented the main methods that are being used in the field of offshore cabling layouts. With the growth of the offshore wind power industry, research has also become more extensive and new techniques have been developed in recent years. However, there are still new paths to be explored in this field. In most of the presented research, the seabed bathymetry is usually not taken into account and could potentially increase the total cable length in a substantial way. Case studies might be interesting to conduct comparing the new proposed collection system voltage (66 kV) with the classic one (33 kV). Finally, both problems of this chapter (Cabling layout and Cable sizing) can be combined to achieve a more general analysis.

Chapter 2
Cabling Layout Design

2.1. Introduction

This chapter develops the core of this thesis by proposing a method to design an optimal cable layout.

The proposed solution assumes a fixed number of wind turbines at fixed locations and a fixed number of substations at variable locations. It should be pointed out that this solution is designed to be coupled in the future with a general stochastic optimization process which will attempt to find the layout of wind farm that minimizes the LCOE. Therefore, for computational purposes, the proposed solution will not develop a nested approach, as described in Section 1.2.2. Instead, a trade-off between optimality and computational cost is done. The design will develop a multi-step approach where a reliable local optimum will most likely be obtained. The multi-step approach consists in firstly solving the wind turbine allocation problem, and then resolve for each cluster independently the cabling layout problem.

The main objective of this optimization is to minimize the total length of the offshore cabling. Once the optimization problem is solved, the sizing of the cables is done by analyzing the supported power of each section.

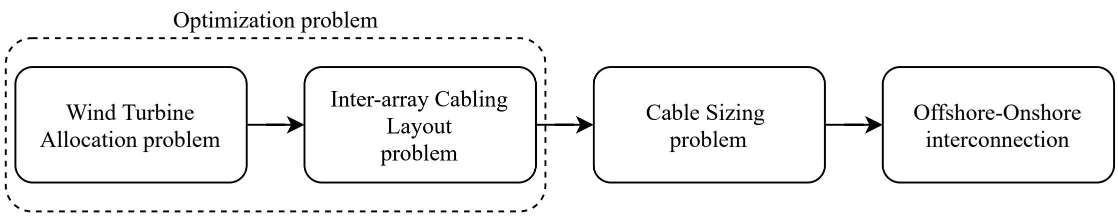


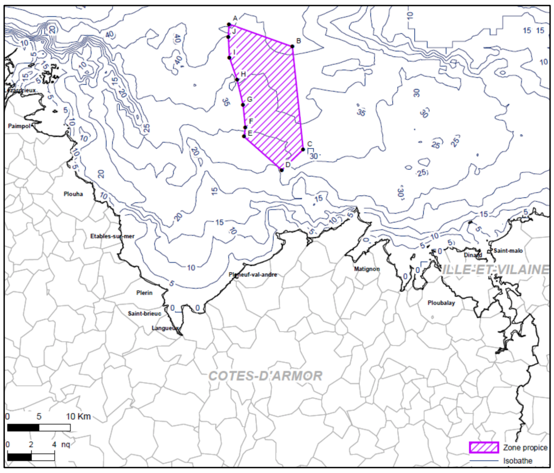
Figure 8 - Multi-step approach of the proposed method. Source: Author

As shown in Figure 8, the method follows a step by step the process: firstly, the process of segmenting the wind farm into clusters will be introduced; then, the graph construction and the search of a minimal length will be explained; and finally, the sizing of the cables are done. As a case study, the data from the Saint-Brieuc wind farm is used to apply this method. The comparison between the solution of this thesis and the real cabling design of St. Brieuc will take place in Chapter 3. Before the explanation of the proposed design method, we will give a brief presentation of the Saint-Brieuc project's geometries and constraints.

2.1.1. Saint-Brieuc wind farm

The St. Brieuc wind farm is currently being constructed by Ailes Marines and projected to be fully operational by the end of 2023 [40]. As can be seen in Figure 9.a, it is located in the North coast of Brittany, a region in the West of France, and the park's geometry and constraints are detailed in the government's Invitation To Tender [41] and is represented in Figure 9.b.

(a) Location of Saint-Brieuc WF



(b) Perimeter of WF defined in [41]

Figure 9 - Location and perimeter of the Saint-Brieuc wind farm.

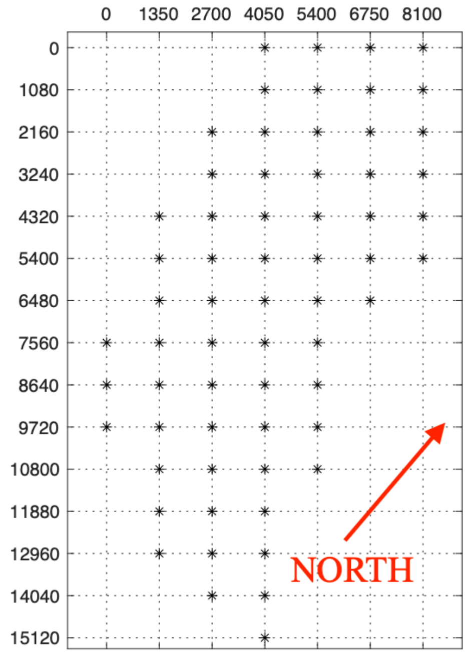
We assume the following constraints for the wind turbines. The nominal power is 8 MW. The inter-array cabling operates at 66 kV while the onshore grid is usually at 225 kV. Therefore, at each offshore substation there is a transformer to increase the voltage.

The maximal power that the wind farm should provide is 500 MW. Ailes Marines, owned 100% by Iberdrola, won the government's Invitation To Tender and the final project will consist of 62 Siemens Gamesa 8 MW wind turbines distributed over a 75 km^2 area with an investment of €2.4bn [42].

The wind farm layout in the following sections (the layout of the wind turbines) has been replicated from the real-life configuration, this will allow a direct comparison between the theoretical method discussed here and the practical design being constructed. The layout of wind turbines is represented in Figure 10. However, as can be seen in Figure 10.b, this layout has been rotated for simplicity reasons. Therefore, in the following, all figures representing the wind farm layout are facing North-West.

This layout of wind turbines is on a grid, and as can be seen in the axis of Figure 10.b, there exists a separation of 1350m in the x-direction, and 1080m in the y direction [43].

(a) Wind Farm Layout from Ailes Marines



(b) Representation of layout in Matlab

Figure 10 - Wind Farm Layout

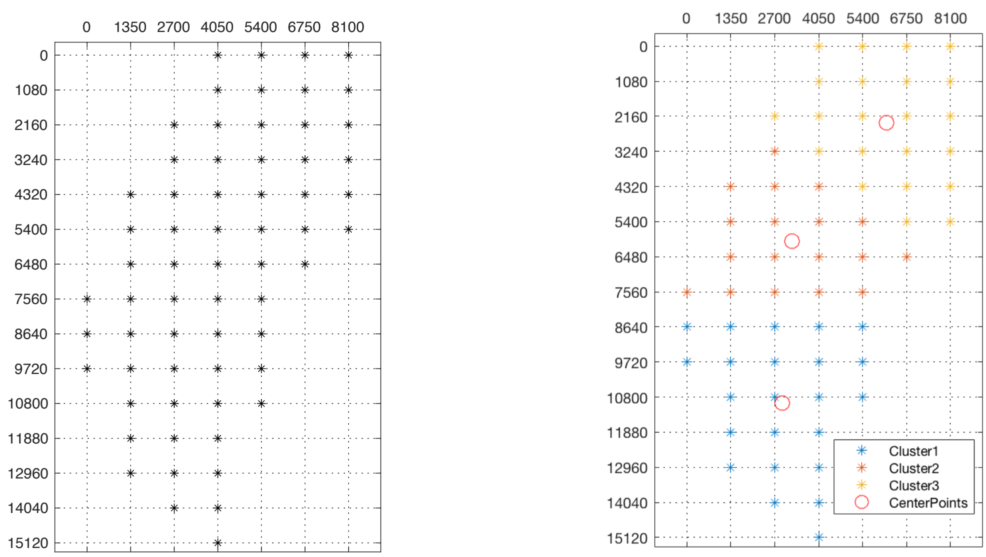
2.2. Wind Turbine Allocation problem

For many large-scale wind farms with several hundred wind turbines, the necessity of having more than one substation arises due to power limits imposed by the characteristics of the inter-array cables and the substation. Therefore, the first step of this method consists in optimally assigning each wind turbine to a single cluster

The fact that the number of offshore substations is assumed predefined decreases the complexity of the problem and therefore a multi-step approach (detailed in Section 1.2.2.) is undertaken where we firstly partition the wind farm and then design the cable configuration for each cluster independently. The kmeans++ algorithm was used to partition the wind farm. The location of each offshore substation is given by the centroids of each cluster together with a series of constraints.

The kmeans++ algorithm, one of the most widely used clustering algorithms, is an improvement to the original NP-hard k-means problem, which consists in finding cluster centers that minimize the sum of squared distances from each data point of a cluster to its center [44].

The algorithm takes as inputs all the data points (in this case, wind turbine locations), and the desired number of substations, and outputs a classification of the wind turbines with respect to each cluster and the centroids of each cluster (i.e., the offshore substation location that minimizes cable length).



(a) Wind farm layout before clustering (b) Wind farm layout after clustering

Figure 11 – Example with 61 turbines and 3 substations.

In Figure 11.a, a layout of wind turbines is represented. Once the clustering problem is solved, the outputs of the algorithm are shown in Figure 11.b.

Placing the Offshore Substations

From the kmeans++ algorithm, the center of each cluster is given. It is therefore a relatively straightforward task to automatically place an offshore substation in a wind farm. However, we impose the following constraints:

- A substation must be placed at halfway points between the wind turbines. This is to ensure that it isn't occupying a possible wind turbine location.

- Due to the added cost of changing the direction of the cables in a wind farm, the priority is to maintain a given cable direction when connecting the substation. This is achieved, in part, by the first constraint. However, there are certain occasions where, in order to reduce the cable length, the cable direction of a section might have to change in order to reach the substation.

Taking these constraints into account, we obtain a grid of available locations for the substation. The objective now is to find, from the available locations, the one that minimizes the distance from the centroid of the cluster given by the kmeans++ algorithm.

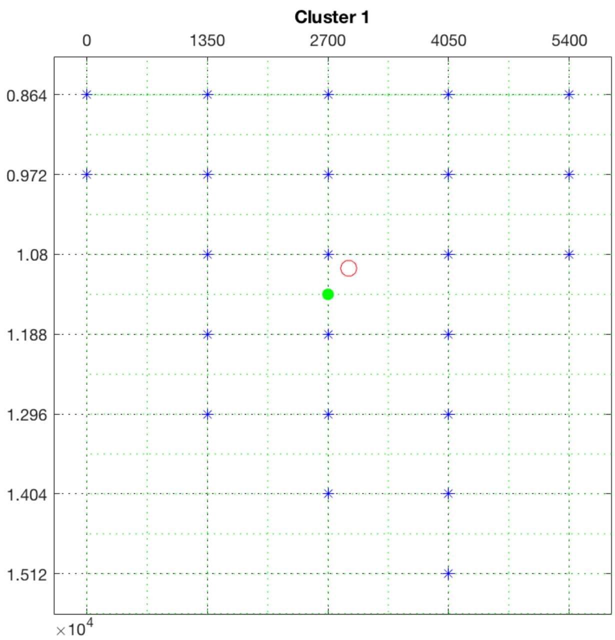


Figure 12 - Representation of Cluster 1. In blue, the wind turbines of cluster 1. In red, centroid of cluster. In green, placement of substation.

The first constraint can be simply verified by analyzing the aerial images of real-life wind farms and focusing on the offshore substation placement. As shown in Figure 13, the substations are usually placed at halfway points in between the wind turbines.

Figure 13 - London Array Offshore Wind farm (UK) (left) and Borselle windfield, Netherlands (right). Source: Getty Images

2.3. Inter-array Cabling Layout problem

Once the wind farm is divided into clusters, and each wind turbine is assigned to a given substation, we proceed in the design of the inter-array cable layout for each cluster independently.

This section corresponds to the problem detailed in Section 1.2.1. of the literature review. In this method, a Minimum Spanning Tree algorithm was implemented to find the optimal path for each cluster. The complexity of this method had to be taken into account due to the general optimization which would be implemented later on. Therefore, the more complex MILP, GIP or GA algorithms weren't feasible for reduced computational times.

The first step in this graph problem is to convert the cluster of wind turbines into a graph. The procedure is to construct an inter-connected graph as shown in Figure 4 where all wind turbines are connected between each other and each edge is assigned a weight representing the distance between the two turbines.

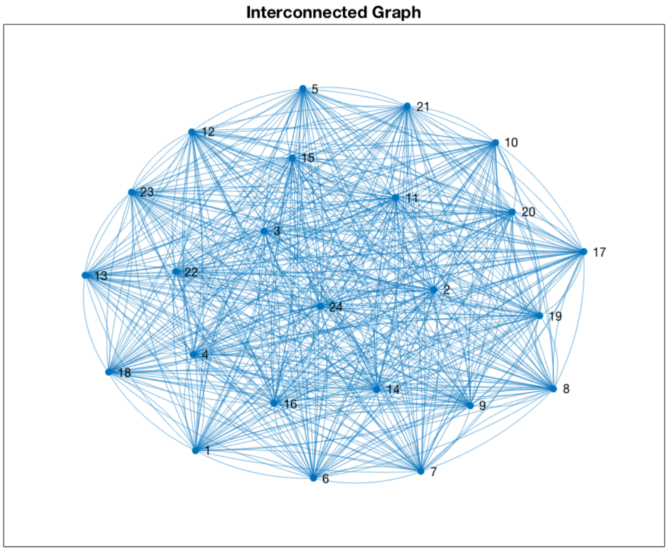


Figure 14 - Interconnected graph of Cluster 1. Node 1 represents substation, nodes 2-22 represent the wind turbines.

2.3.1. Considering Bathymetry

As was explained in Section 1.2.1.1. of the literature review, the consideration of the seabed underneath an offshore wind farm is quite rare when designing the cable layout and calculating cable costs. It is therefore interesting to consider it in this study.

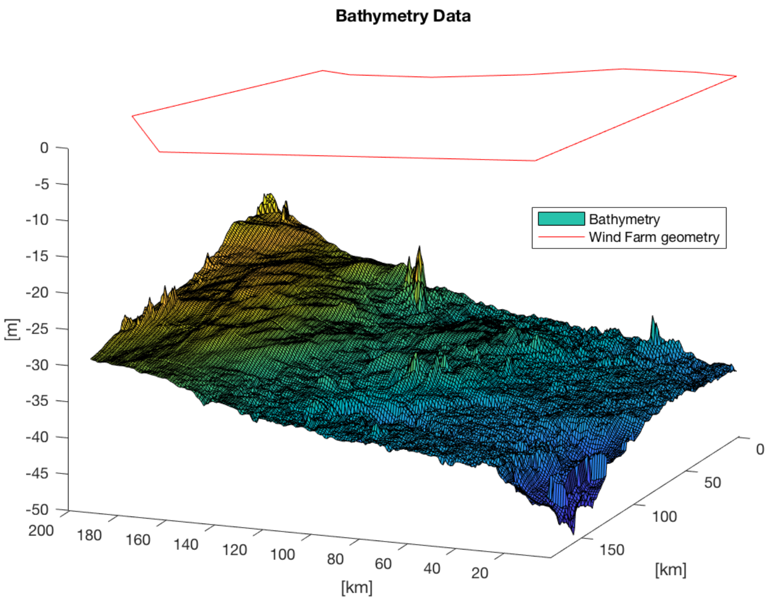


Figure 15 - Bathymetry Data of St. Brieuc Wind Farm

As can be seen in Figure 15, the bathymetry data has been obtained for the St. Brieuc bay and can therefore be analyzed. This figure is not proportional and only serves for visual purposes, as the x and y axis are in kilometers while the z axis is in meters. Even though, in reality, the added total length of inter-array cabling might be only a few kilometers when considering the bathymetry, this translates in a non-negligible cost, due to the elevated costs is undersea electrical cables.

*   *   *

In the following, we will use basic graph theory vocabulary to explain our proposed layout:

- Node: can indicate a wind turbine or the offshore substation. Each node is identified by an individual number. The convention taken in this study is: the first node (node=1) represents the offshore substation, and the rest are the wind turbines (nodes=1…n).
- Edge: it is the connection between two nodes, it is therefore the representation of a cable on the wind farm.
- Weight: it is a number associated to each edge and represents the length between two nodes.
- Other graph properties: Any number of properties can be added either to the nodes or edges. This will be useful in the dimensioning section that will be detailed further on.

Once the construction of the interconnected graph is complete we can start the optimization process of finding the best layout of cables which minimizes the total inter-array cabling distance.

As for the Minimum Spanning Tree (MST) problem, algorithms such as Kruskal, Prim, Dijkstra or A* exist. All of these algorithms run in polynomial time and all but the latter are greedy algorithms. In the proposed method, the MATLAB function *minspantree* was used due to its implementation simplicity and the desired results obtained. Another important aspect is the fact that it minimizes the global length of the graph, instead of individual node by node minimizations such as the Shortest Path Algorithm.

This algorithm takes as inputs the graph shown in Figure 14and a root node from which the tree starts. As the root of the graph is the offshore substation (node id = 1), and as it is placed at the center of the cluster, the power flowing in each cable connected to the substation should be (equally) distributed. Once the algorithm finds an optimal solution, the output is a graph similar to Figure 16.

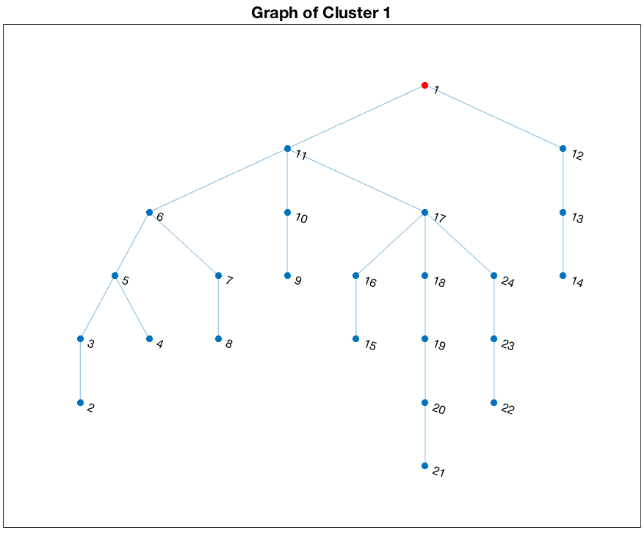


Figure 16 - Minimum Spanning Tree of Cluster 1.

By repeating the process for each cluster, we obtain the inter-array cable layout of the whole wind farm that minimizes the cable length for each cluster (Figure 17). As a reminder, this layout is obtained for a fixed configuration of wind turbines and a fixed number of clusters.

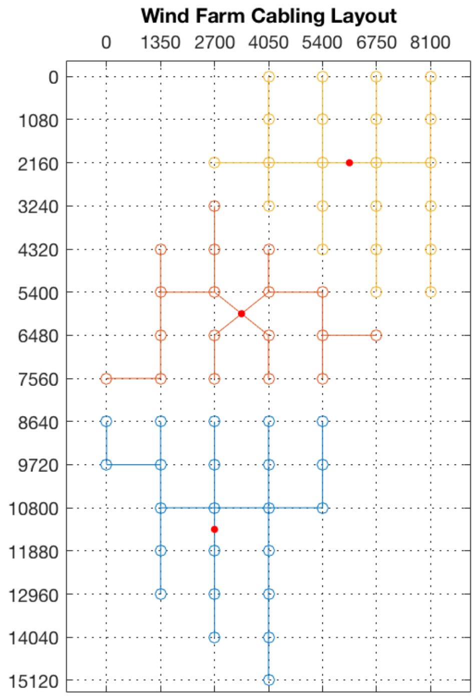


Figure 17 - Cabling layout of Wind Farm with 3 clusters. The three red dots represent the offshore substations.

2.4. Cable Sizing

In this section, we calculate the appropriate cable sections for each edge by evaluating the nominal power that, in theory, could flow through each connection. This process follows the Static Rating method described in Section1.3. This is therefore not part of the optimization process, and it is done once a solution from Section 23 is reached.

First, we take the nominal power of a single wind turbine. We assume that the maximal power that can flow through a given edge is the sum of all the nominal powers of the child nodes (all the connected nodes further from the root than the given edge).

To visualize this in a clearer way, Figure 18 represents the dimensioned cabling with the power shown at each edge (in MW). In Figure 18 each color represents a different type of cable, chosen from a given datasheet with all the possible cable types and their characteristics. As the nominal power for each wind turbine is 8 MW, it is easily verified that the cables at the extremities of the graph are supporting only one wind turbine and as we pass to the parent nodes, the power is the sum of the children nodes (the ‘deeper’ wind turbines), as represented on the edge labels of Figure 18.

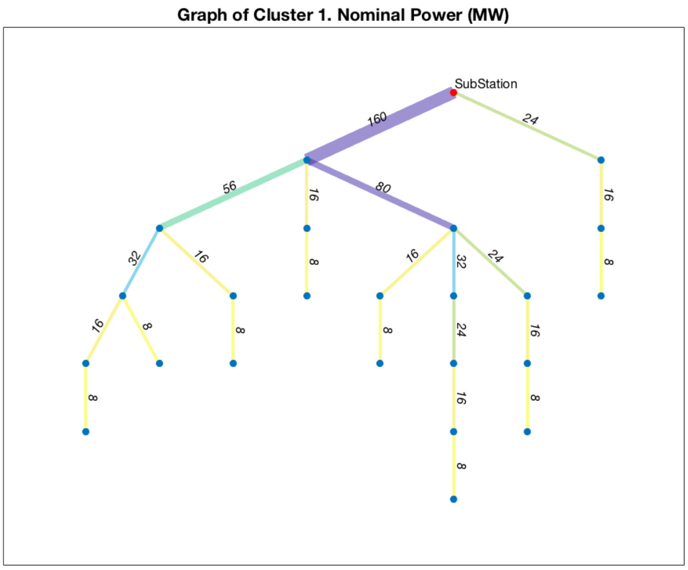


Figure 18 - Dimensioned cabling layout. Nominal power represented on edges. Example for 8 MW nominal power

However, for cables operating at 66 kV as is the case with the inter-array layout, sometimes the largest possible cable isn’t sufficient to meet the power demands, especially for the connections located near the substation. The solution is to install several cables in parallel. In Figure 8 the number of cables per edge is represented and we can see that the connections to the substation usually require more than one cable per edge.

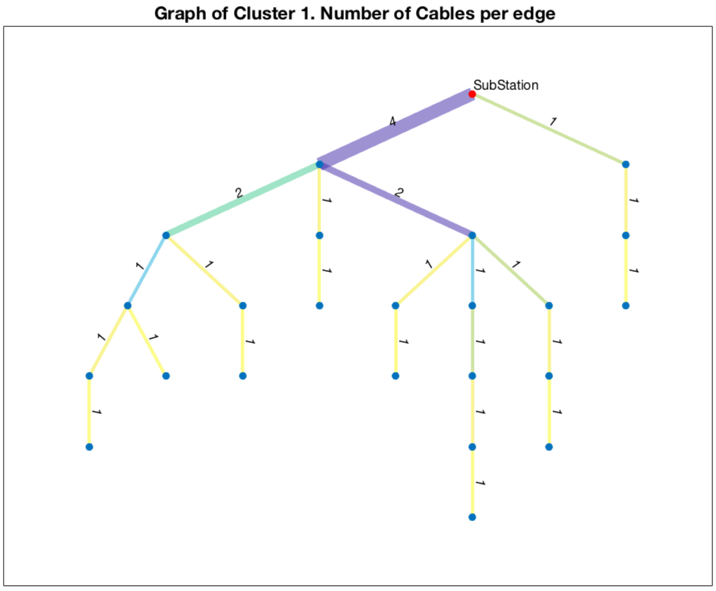


Figure 19 - Dimensioned cabling layout. Number of cables represented on edges.

2.5. Offshore-Onshore Interconnection

In this section, we design the transmission cabling from the offshore inter-array cabling that has just been designed to the main grid on land.

This section corresponds to the problem described in Section 1.2.4. However, in our case, the connection to the onshore substation is done in a straightforward manner considering multiple onshore substations and one single onshore substation. Therefore, the problem of multiple onshore substations is not considered for practical reasons, and the problem becomes a simple task.

As the inter-array cabling is at 66 kV and the onshore grid is at 225 kV, the cable connecting the offshore to onshore substations is at 225kV and by computing the power that has to flow through it, we can choose an appropriate cable that will support the specific demands.

The selection of the onshore substation is done by searching the national grid's available substations. In our example of the St. Brieuc wind farm, we search on a website that shows the connection points and high-tension grid in France [https://www.capareseau.fr] and find that the Doberie substation is the closest link to the offshore wind farm. It is interesting to point out that the real project being developed is using the Doberie substation, as we can see in Figure 20 the 225 kV cable that connects the inter-array cabling to the grid.

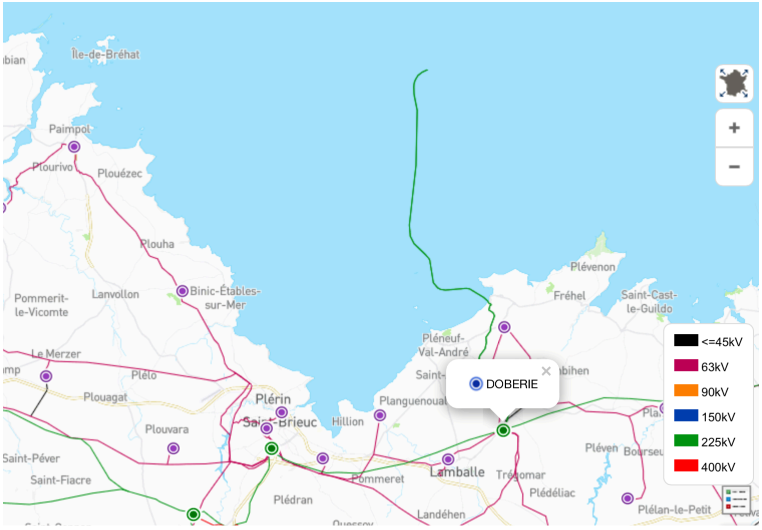


Figure 20 – High tension lines and connection posts in the bay of St. Briuec. Doberie substation highlighted.

Once we retrieve the coordinates of the closest onshore substation, we can calculate the length of the cable that is needed to link the offshore to the onshore substations. After this is done, we obtain a complete design of the cable layout of an offshore wind farm, as shown in Figure 10.

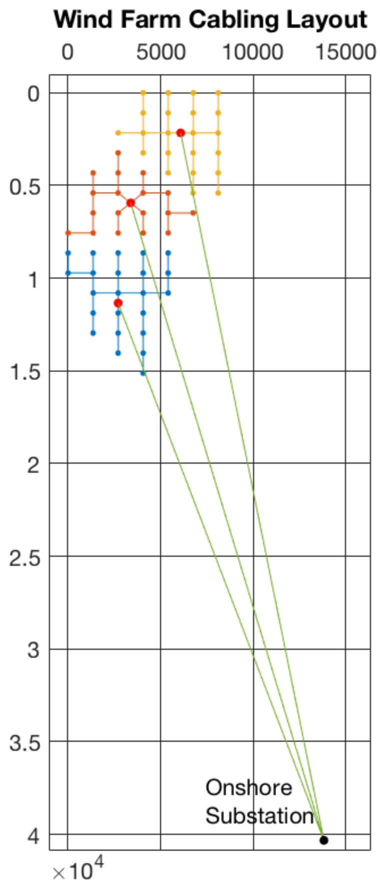


Figure 21 - Wind farm inter-array and transmission cabling layout.

2.6. Summary

In this chapter we have presented a method to optimally design an offshore wind farm cable layout. By using optimization algorithms such as kmeans++ or MST, we can be confident the given solution is a reliable optimal one for the problem we were dealing with, even though it might not be the global optimal solution, which would take too much computational time. We have therefore developed an efficient method which can be easily coupled with larger optimization problems.

Chapter 4

Discussion

In this chapter we analyze the proposed solution presented in this study and compare it to the existing literature and to the real-life solution of the Saint-Brieuc wind farm project.

4.1. Comparison with Saint-Brieuc Wind Farm Cabling

In this section, the real-life solution for the Saint-Brieuc wind farm project is detailed. There exist certain aspects of the design which differ from the method of Chapter 2, and it is interesting to underline the reasons for these differences.

Firstly, it can be seen in Figure 22 that the geometry has changed from the initial ITT geometry. This is due to certain constraints that have appeared as the project advanced, such as a protected fishing area (in orange in Figure 23, to the South), and an environmentally protected area (in green in Figure 23, to the South-East).

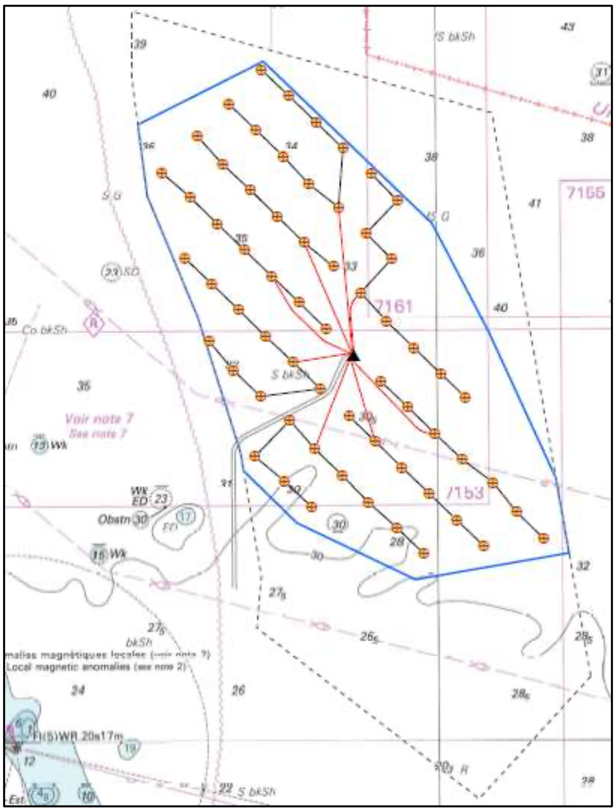


Figure 22 - Cable layout design developed by Prysmian Group. Source [43]

It can also be observed that the wind farm is not partitioned, and only has one substation. This is because the wind farm only has 62 wind turbines and it is therefore a relatively small wind farm. In the solution developed in Chapter 2, the method is envisioned to be as general as possible and therefore considers the possibility of partitioning.

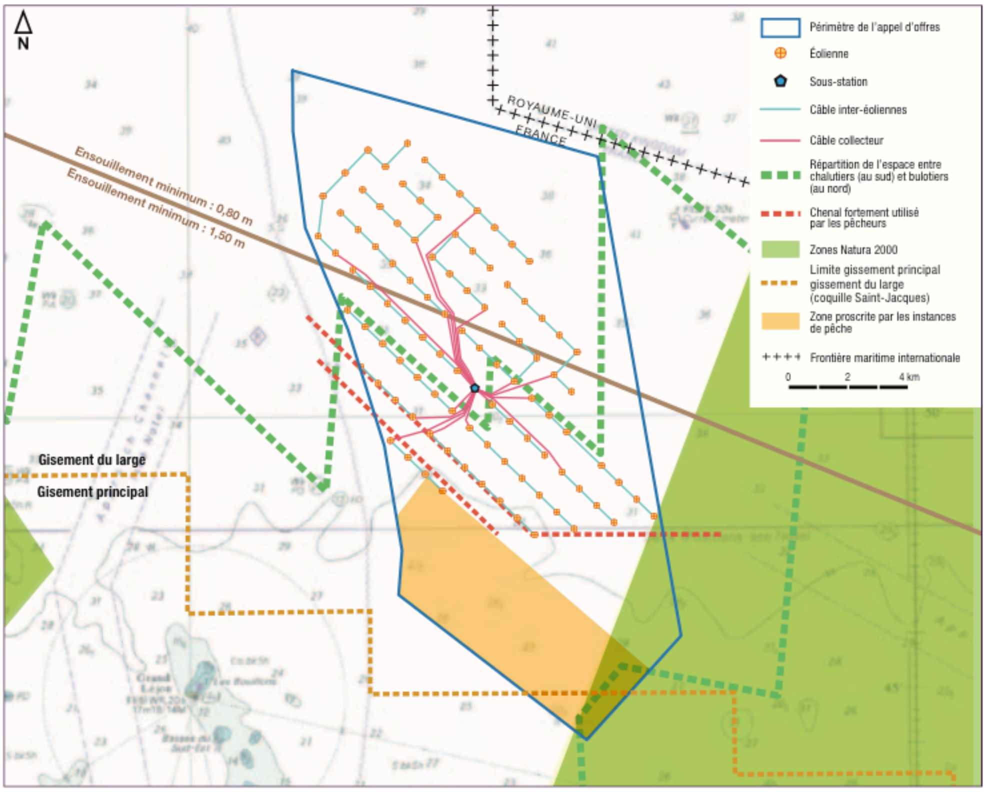


Figure 23 - Initial cable layout design developped by PrysmianGroup (2013). Source [45]

Fishing constraints play a main role in the real-life design of the wind farm cabling. In the area of the wind farm there are two types of fishing: in the north passive fishing is allowed where boats remain static; in the south of the park, active fishing is practiced where boats move to catch fish via dragging nets [45]. This affects the geometry of the cabling and it is the reason why the south of the park presents more parallel lines, easier for navigation, and the north of the park has a more complex geometry. Moreover, the doted red line in Figure 23 indicates an important fishing lane in the area, and therefore the cable lines have to be parallel to the lane's direction.

To furthermore meet the fishing community's demands, the cables are planned to be inserted 1.5m below the seabed. This is done to prevent the fishing nets from tagging the cables that would potentially damage the cable or produce a security hazard.

Another characteristic of the cable layout design is that the wind turbines are grouped into clusters of 9, and only two types of cables are used: the cables connecting the wind turbines, and a cable connecting each cluster to the offshore substation. This is most likely done to design a flexible geometry that meets all the constraints; but it will also help the logistic costs, simplifying the transport and installment of different cable types.

As can be seen comparing both designs (method from Chapter 2 and real-life design) many constraints that have to be considered in real-life situations are very difficult to generalize, because they strongly depend on the location of the wind farm. However, we can see similarities and a motivation to optimize the design in order to minimize costs.

Conclusion

In the developing industry of the offshore wind energy, it is more important than ever to find and develop new innovations that allow for a more efficient and cheaper energy, which will in turn help the industry become more dynamic. In this sense, this thesis has studied an important part of an offshore wind farm: the electrical infrastructure.

A review of the most recent methods and studies was presented, where the state of the art of the industry was analyzed and compared. The cabling layout was divided into two subproblems (configuration and sizing) and, for each one, the different techniques were detailed. For the cabling configuration, we saw that a majority of MILP and BIP formulations were being used while GA were gaining momentum. In the sizing problem, three techniques were presented: the industry standard and two more complex statistical methods.

As for Chapter 2, the cabling design method of this study was presented. A step-by-step process was detailed where, from a given configuration of wind turbines and a given number of offshore substations, an optimal cabling layout was conceived while remaining in sufficiently fast times. Once the cabling configuration had been designed, the layout was dimensioned using a similar technique to the industry standard. In Chapter 3, the power flow of the park is presented in order to asses to losses and compensations of the grid.

Finally, in Chapter 4 a discussion into the design was undertaken. Firstly, a comparison between algorithms was made in order to choose the most appropriate one for the method of Chapter 2. After that, a comparison between the literature and the proposed method was detailed where a series of similarities were pointed out, such as the use of the multi-step approach or the static rated sizing. In the last section of this chapter, the real-life Saint-Brieuc design was presented, with interesting conclusions on the constraints that had to be taken into account.

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