Offshore Substation Locating in Wind Farms Based on Prim Algorithm

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***Abstract*— The investment of offshore wind farm is large while the cost on electrical system can take up to 15% of the total costs. In order to reduce the cost, it is desirable to optimize the electrical system layout in design phase. Since the location of offshore substation (OS) is highly related to the electrical system layout, the optimal layout design work should be done with the consideration of the impact of the location of offshore substation on the submarine cable connection layout to minimize the investment of cables. This paper addresses a new method to optimize the OS location together with the cable connection layout. The results show that the proposed method is an effective way for offshore wind farm cable connection layout design.**

***Index Terms*—electrical system layout; offshore substation (OS); submarine cable.**

Nomenclature

C_i [MDKK/km]	the unit cost of cable i
$S_{n,i}$ [W]	the rated apparent power of cable in line i
A_p, B_p, C_p	the coefficient of cable cost model
$I_{i,rated}$ [A]	the rated current of cable in line i
$U_{i,rated}$ [V]	the rated voltage of cable in line i
x, y	the position of OS in the form of coordinate
$C_i(x, y)$ [MDKK/km]	the unit cost of cable i when OS location is (x, y)
$L_i(x, y)$ [km]	the length of cable i when OS location is (x, y)
$Q_i(x, y)$	the number of cable i when OS location is (x, y)
$C_{tol}(x, y)$	the total cost of cables when OS location is (x, y)
N	total number of vertices in a graph
I_i [A]	the current going through the cable i
L_x [km]	the width of wind farm in horizontal direction
L_y [km]	the length of wind farm in vertical direction

I. INTRODUCTION

The offshore wind farm has a larger power capacity factor and occupies larger area compared with onshore wind farm. In such a wide region, the power generated from each Wind Turbine (WT) is first collected through a series of medium voltage (MV) cables and be transmitted to the OS by one or several MV integration cables. The voltage is transferred to a transmission voltage level so that all the power can be transmitted to the onshore substation through transmission system. Due to the limitation of cable current carrying capacity, the cable size should be carefully selected. Since the location of the substation would have a significant impact on the collection system layout which contributes to the total investment of electrical system, it is necessary to design the cable connection layout considering OS location to save investment on cables while meet the operating requirement.

The assessment of offshore wind farm layout has been done in [1] for comparing AC and/or DC collection systems (CS) corresponding to different voltage levels. Further, the collection system with different topology was compared in [1]. The electrical system is optimized concerns both the production cost as well as reliability in this paper. In [3], a new algorithm to minimize the system power losses and improve the reliability was proposed and validated through a small reference wind farm. Based on a practical wind farm project, the Fuzzy C-means clustering algorithm was adopted in [4] to partition the whole system into several subsets. The substation was regarded to be located in the center of each subset and the cable connection layout in each part was optimized with Minimum Spanning Tree (MST) algorithm to get a minimal investment of collection system. The MST is also utilized and modified in [6]. The layout with minimal trenching length is found. The maximum number of WTs that can be connected after one cable is considered. The power flow is also computed to help assign the cable size. In addition, Generic algorithm (GA) was also widely used in finding optimal cable connection layout [6][7]. The topology design, electrical system voltage level as well as key components selection are included in [6]. It succeeded in optimizing the electrical system layout with the minimal Levelised Production Cost (LPC) while reaching the reliability requirement. The optimal collection system is also presented in [7]. It attempt to use GA to find the minimal cost cable connection layout for a 4 substation offshore wind farm and several layouts are compared to demonstrate the effectiveness of the new method.

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In this paper, the offshore wind farm collection system layout is optimized by prim algorithm. Since the location of OS is highly related to the collection system layout, the siting of the OS is optimized together with the system layout to minimize the total investment on electrical system. In order to meet the system operation requirement, the cable current carrying capacity is considered in cable selection process during the simulation. The proposed method is implemented in a regular and an irregular shaped wind farm and the results show that it is an effective way for offshore wind farm electrical system layout design.

The prim algorithm for the optimization problem, cost models and optimization framework are specified in section II. A regular and an irregular shaped wind farm both with 80, 2MW WT are chosen as the study cases to demonstrate the proposed method in Section III. Finally, conclusions and future work are given In Section IV.

II. PROBLEM FORMULATION

In this section, the MST problem and prime algorithm are firstly introduced. Then the cost model which is used in this work is specified. Finally, the optimization framework and some assumptions are proposed.

A. Minimum Spanning Tree

A tree is defined as a connected acyclic graph [7]which is one sub graph of the undirected graph. The spanning tree can be defined as a sub graph of an undirected weighted graph which connects all the vertices with merely one path between every two nodes while the minimum spanning tree is one of the spanning trees with minimum weight [8]. If the location of WTs and OS can be regarded as vertices while the costs of the cables are regarded as the weight of branches. Then, the problem can be converted into a classic mathematical problem as finding the MST of a weighted graph.

B. Prim Algorithm

Presently, prim algorithm and kruskal algorithm, which are both based on the idea of greedy algorithm, are commonly used in solving MST problem [9]. In this work, the prim algorithm is adopted to get the collection system layout and modified to include the optimization of OS location. Generally, the prim algorithm proceeds as follows [10]:

(1) Selecting any node V in the graph as the searching starting point.

(2) Constructing two sets, A and B. Adding the rest vertices in the graph into Set A which stores unvisited vertices within the graph.

(3) Comparing the weight of all the branches that connect to V and select the minimum-weight branch as the generated tree branch in this step. The other vertices of this branch will be added to Set B and deleted from Set A.

(4) If Set A is empty, the program will stop. Otherwise, go to step 3 until the MST is completed.

C. Cost model

The cost models are set up according to cables' rated power. The mathematical equations can be written as [11]:

$$C_i = A_p + B_p \exp\left(\frac{C_p S_{n,i}}{10^8}\right)^2 \tag{1}$$

$$S_{n,i} = \sqrt{3} I_{i,rated} U_{i,rated} \tag{2}$$

The cables are selected according to its rated current which is correlated to the sectional area in this paper. In some cases, more cables are required between two WTs if too many WTs are connected after this branch. Then the total cost of cables can be calculated by the following equation.

$$C_{tol}(x, y) = \sum_{i}^{N} C_i(x, y) L_i(x, y) Q_i(x, y) \tag{3}$$

D. Optimal cable connection layout by modified Prim algorithm

In this project, the optimal location of OS should be found together with the optimal collection system layout. It can be solved by introducing one more element of substaion location into the graph and the location of OS is selected as the searching starting point. The optimization framework is shown in Fig. 1.

Cable Database: In [12], various voltage levels' cables with different sectional areas can be found. In this simulation, the cables in the wind farm are XLPE-Cu AC cables operated at 33kV nominal voltage for collection system and one 132kV 715 mm^2 HVAC cable is selected for transmission system.

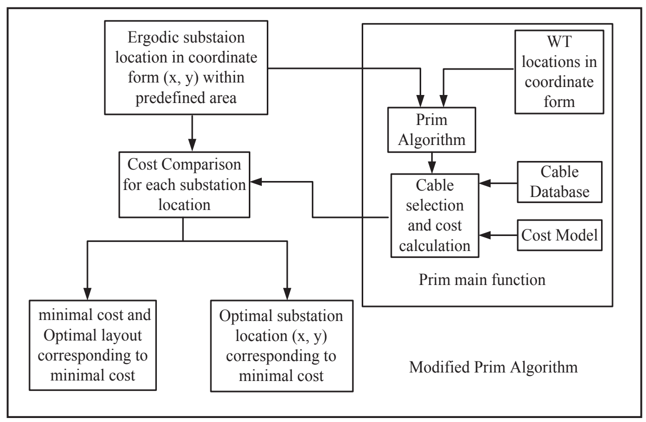

Figure. 1. Optimization framework

The locations of WTs and onshore substation are assumed to be fixed in this project. The optimal location of substation is expected to be found within the predefined area. Each time, a new OS location is loaded, a new coordinate matrix which contains the coordinate of WTs and OS will be created. Based on it, the optimal cable connection layout will be found by using prim algorithm which is discussed in Section II.B. Since the transmission capacity limitation, the cable size of each branch should be carefully selected. The Cable Database contains the available cable size. From the number of WTs connected to the branch, the maximum current going through the cable could be calculated. After that, the total cost could be calculated using (1), (2) and (3).

Since the location of OS is given ergodicly. A series of costs should be compared in cost comparison step so that the minimum cost layout could be selected which is the optimal cable connection layout. Finally, the minimal cost electrical system layout as well as the location of OS will be found at the same time.

E. Assumptions

Some necessary assumptions for the optimization problems are:

- The lengths of the cables are selected according to the geometrical distance without thinking of practical usage, such as the barriers, restriction in sea, etc.
- The position of OS (x, y) is permitted to be constructed within a prespecified area, that is, $x \in (0, L_x);\ y \in (-10, L_y)$.
- Due to the cable current carrying capacity limitation, the current in each cable cannot over its limit, that is, $I_i \leq I_{i,rated},\ i \in (1, N)$.

III. Case Study

The simulation is implemented on the platform of Matlab software. Two study cases are adopted to verify the feasibility of the proposed method.

A. Case I: Regular shaped wind farm

The wind farm is assumed to be set up 30km away from the coast with 80, Vestas V90-2.0 MW (90m rotor diameter) WTs which can be seen in Fig. 2. The locations of WTs are predefined within a 7D*7D regular shaped wind farm which means that the distance between each two WTs are 7 rotor diameters. Four scenarios are presented and compared with obtained optimal layout.

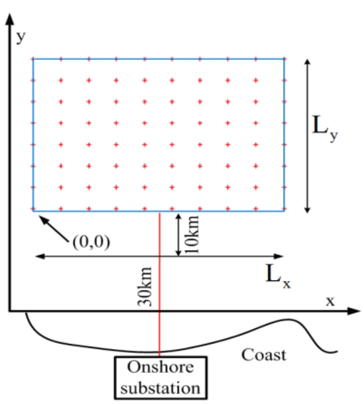

Figure. 2. Regular shaped wind farm

In Fig. 2, the red star shows the locations of WTs. The blue square is the boundary of the predefined wind farm area. The substation is permitted to move from 0 to L_x in x direction and -10 to L_y in y direction. The cable within the blue square area and the cable which transmit the power collected from all WTs to OS constitute the collection system. It can be seen that if the OS is moving closer to the coast, the investment on HVAC cable will be reduced, however, the investment on collection system's cables should be higher and it will be just contrary if the substation is constructed inside the blue square area. There should be a tradeoff between these two parts' costs.

1) *Scenario I: Industrial offshore wind farm layout:* In this scenario, the industrial 7D layout is introduced. As can be seen in Fig. 3, the red starts indicate the WTs' location and the green lines show the integration cables which transmit the power from WTs to OS (the blue square) while the black lines show the cable connection layout. There are totally 5 integration cables in this layout. Each integration cable has the capability of transmitting the power generated by 16 WTs in full load condition. The WTs are placed with 7 rotor diameters interval in both x and y direction and the OS is 25 km away from coast.

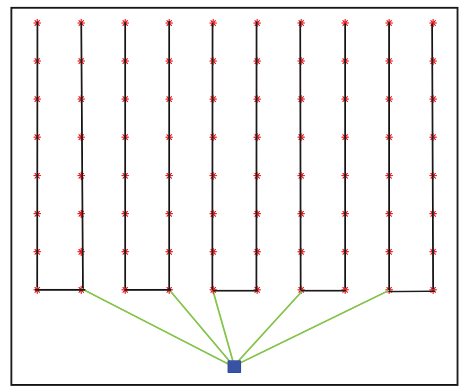

Figure. 3. Industrial 7D layout

2) *Scenario II: OS near shore layout:* In this scenario, the OS is assumed to be constructed 25km away from coast. Then the cable connection layout could be found by the proposed method. The input to the coordinate matrix is just one given location of OS instead of a series of locations in this case. The optimal layout is illustrated in Fig. 4.

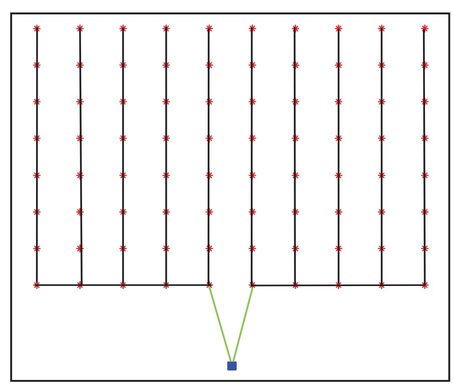

Figure. 4. Optimal layout for OS near shore

3) *Scenario III: OS in the center layout:* In this scenario, the OS is assumed to be constructed in the middle of wind farm. The optimal cable connection layout found by the proposed method for this scenario is illustrated in Fig. 5.

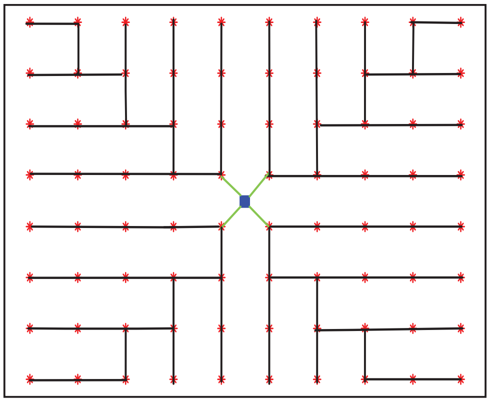

Figure. 5. Optimal layout for OS in the center of wind farm

4) Scenario IV: Optimal collection system layout: In this scenario, the OS location is expected to be found together with the optimal cable connection layout. Following the proposed optimization framework in Section II. D, the optimal layout is shown in Fig. 6. In order to see the performance of the proposed method, the layouts are also compared in Table I.

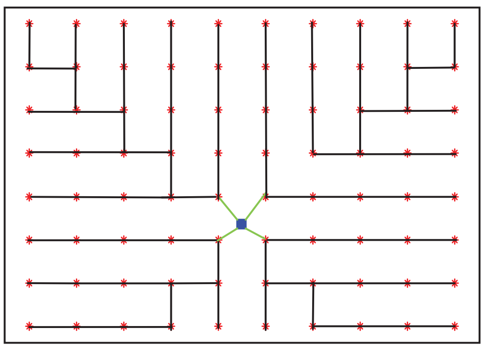

Figure. 6. Optimal collection system layout for regular shaped wind farm

TABLE I. LAYOUT COMPARISONS FOR REGULAR SHAPED WIND FARM

	Scenario I	Scenario II	Scenario III	Scenario IV
Total cable length for CS (km)	73.37	72.96	49.67	50.95
Trenching length for CS (km)	73.37	54.78	49.67	49.75
Cable to shore (km)	25	25	32.21	31.38
Cable costs for CS (MDKK)	118.10	131.31	68.39	137.64
Cable costs for TS (MDKK)	103.75	103.75	133.65	135.91
Total Cable invest (MDKK)	221.85	235.06	202.04	199.02
Substaion location	(2.84,-5)	(2.84,-5)	(2.84,2.21)	(2.84,1.38)

In Table I, the trenching length indicates the total single line distance between WTs while cable length is the total cables that should be laying in this layout. It can be seen that the cheaper layouts should be Scenario III and IV. The cable length is longer than trenching length for Scenario II and IV which means that more than one cable is needed between two WTs in some parts in these layouts.

Compared with Scenario I, Scenario II is more expensive. In spite of saving the invest on the cables which collect all the power from WTs and transmit it to the OS, in the layout of Scenario II, more than one cable has to be utilized between WTs to meet the operational requirement which increases the total cost eventually.

The minimal cost layout is Scenario IV. However, it is preferable to have only one cable between WTs as Scenario I and III layout in practical. Since more cables operating in parallel means the invest on trenching and electrical components will be doubled.

B. Case II: Irregular shaped wind farm

In this section, an irregular wind farm with 7 rows and 14 columns is chosen as the studied wind farm. In this wind farm, there are totally 80, Vestas V90-2.0 MW WTs which are placed with a nearly rhombus shape. The distance between WTs in both x and y direction are 7 rotor diameter (7D) as well which can be seen in Fig. 7.

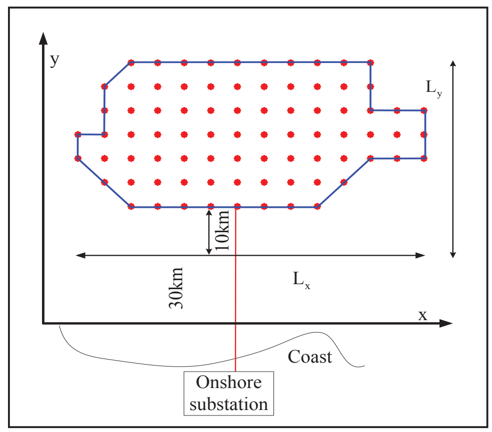

Figure. 7. Irregular shaped wind farm

The onshore substation is also assumed to be 30 km away from wind farm. Three optimal layouts for this case are shown in Fig. 8, 9 and 10. The specifications of these optimal layouts are concluded in table II.

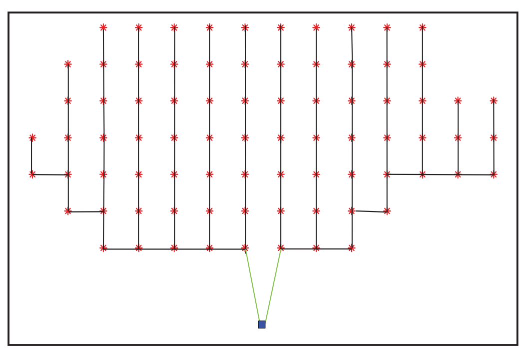

Figure. 8. Optimal layout for OS near shore for irregular wind farm

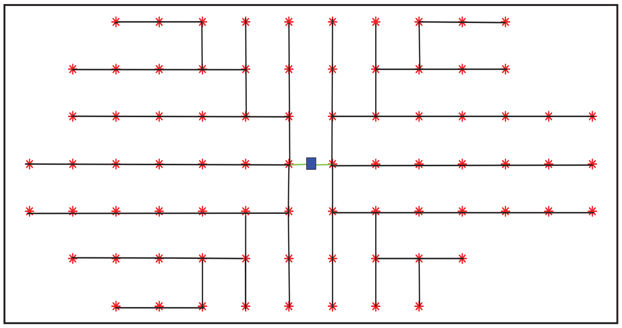

Figure. 9. Optimal layout for OS in the center of irregular wind farm

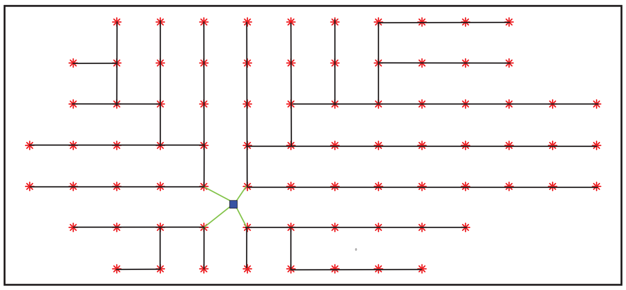

Figure. 10. Optimal collection system layout for irregular shaped wind farm

TABLE II. LAYOUT COMPARISONS FOR IRREGULAR SHAPED WIND FARM

	Scenario I	**Scenario II**	**Scenario III**
Total cable length for CS (km)	72.96	50.4	51.26
Trenching length for CS (km)	54.78	49.77	49.74
Cable to shore (km)	25	31.89	31.10
Cable costs for CS (MDKK)	136.21	70.12	70.27
Cable costs for TS (MDKK)	103.75	132.35	129.07
Cable invest (MDKK)	239.96	202.47	199.34
Substaion location	(4.1,-5)	(4.1,3.78)	(2.96, 1.08)

The graphic in Fig. 8 is the obtained optimal layout when OS is planned to be constructed near shore, while Fig. 9 and 10 represent the optimal layout with central placement of OS and optimal layout with optimal OS location. Similar conclusion can be made that the layout should be more cheap if the substation is constructed somewhere within the wind farm. The Scenario III save the investment of cables for 16.93% and 1.55% compared with Scenario I and II, however, constructing the offshore wind farm far away from the shore may increase the cost of foundations. Hence, more factors as varying foundation cost with water depth, cable installation cost, operation and maintenance cost, etc. should be considered to make the layout more practical so that a comprehensive decision can be made.

IV. CONCLUSIONS AND FUTURE WORK

In order to reduce the cost and make the wind farm more competitive in electricity market, it is necessary to make a cost-effective electrical system layout under the system operational requirement. Within numbers of cable connection layouts, it is expected to find the minimal cost one with no cross cables. This description corresponds to the classic MST problem in graphic theory. Based on it, a new method is proposed to find the optimal electrical system layout for offshore wind farm. Some factors such as the best location to build up the OS and the suitable cable sectional area for each line between two WTs are considered in this paper. The studied cases demonstrate that the proposed method is an effective way to find the minimal cost collection system layout considering cable power transmitting limitation for regular/irregular shaped wind farm. In future, the work can be extended from two aspects: one is to include variable of the number of OSs into the optimal layout design problem to get a more optimal result, the other is to taking the energy yields as well power losses along the cables into consideration to evaluate the layout performance.

ACKNOWLEDGMENT

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