Electric System Layout Optimization of Offshore Wind Farms

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***Abstract* – This paper aims to minimize the total investment and operating cost of electric system of a large-scale Offshore Wind Farm (OWF). An optimization problem is formulated that simultaneously optimizes the electrical configuration and cables size (cross-sectional area) of the interconnection and transmission systems, and offshore components such as HV and MV switchgears, offshore substation platforms and transformers. Moreover, apart from the total investment cost, the annual cost of electrical power losses is incorporated into the objective function as an operating cost forming a multi-objective optimization problem. The problem is then solved by an integer-based genetic algorithm. In order to demonstrate the effectiveness of the proposed algorithm, the obtained optimal results are compared with another study for a real OWF, under identical conditions and constraints. Simulation results show that the obtained optimal electric configuration in this paper results in a lower total investment cost and power losses.**

Keywords - Offshore Wind Farm (OWF); optimal electrical connection layout; Genetic Algorithm.

I. INTRODUCTION

Wind energy is a mainstream renewable source and will play a leading role in de-carbonization. Wind industry, especially in offshore area, demands extensive optimization challenges and technical developments to reduce the Levelized Cost of Energy (LCoE) to allow large-scale Offshore Wind Farms (OWFs) integrate into the power system. The estimation for LCoE reduction of OWFs by 2030 is about 100 $/MWh [1]. The costs of offshore foundations, installation and maintenance, as well as the costs of the electrical interconnection and transmission systems of OWFs are comparatively higher than its onshore counterpart [2], [3].

In order to decrease LCoE of OWFs, optimization of the electric system layout is of significant importance. This includes optimizing the electrical configuration and subsea cables size of interconnection and transmission systems, and the rating of the offshore components such as Offshore Substation (OS) platform, transformers and switchgears. This optimization problem, which is called electric system layout optimization, is very complex and challenging due to its vast search space.

Fig. 1~~Fig. 1~~ indicates the trend in the cumulative capacity of worldwide OWFs between 2011 and 2017 [4], showing an increment of 116% in last three years and a new record by installation of 4.33 GW just in 2017. Nevertheless, offshore wind technology is still in its nascent stage, in contrast to the 520.8 GW worldwide capacity of onshore wind energy.

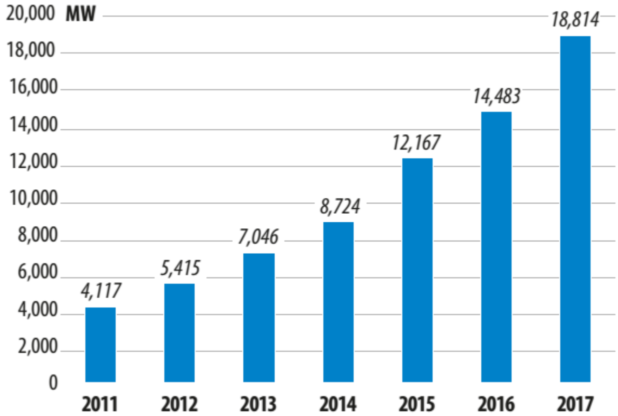

Fig. 1: Global annual cumulative installed capacity of OWF (2011-2017)

In this decade, several research works have recently been conducted on the optimization of AC electric system layout of OWFs [5-15]. Some studies start dealing with this optimization challenge at the beginning of this century. They only found the optimal electrical interconnection configuration of off- and on-shore wind farms in order to minimize the total cables trenching length, while cables size were not considered in objective function and thus analytical optimization methods could be utilized to solve. Dutta and Overbye in [5] proposed different clustering methods to find the optimal interconnection configuration of on-shore wind farms, and then they adopt the Minimum Spanning Tree (MST) algorithm in [6] after decreasing the problem size by some clustering methods. References [7], [8] utilized Mixed Integer Programing (MIP) and reference [9] used a Mixed Integer Linear Programming (MILP) to minimize the total trenching length of OWFs in order to find the optimal interconnection configuration of OWFs. However, the cables size could be incorporate into the objective function of the above mentioned references as analytical optimization methods were utilized, since these methods may fail to find the optimal solution of the problems with variable cost edges. Thereby, metaheuristic optimization algorithms were applied to the recent research works. A modified traveling salesman problem was proposed in reference [10] in order to design a radial configuration of interconnection system for a real OWF. An improved Genetic Algorithm (GA) was used in this study to find the optimal electric system layout of a large-scale OWF, while subsea cables size were also considered without any tapering in a radial configuration. In addition, not avoiding the crossing of subsea cables makes it impractical for burying subsea cable. Reference [11] used a binary GA in order to find the optimal layout of interconnection and transmission systems, and offshore components of an OWF. However, the optimal layout was found with applying some clustering methods for nodes so that the problem size decreases and then solved by a MST algorithm. The authors in [12] utilized an integer-based GA to find the optimal electrical configuration and cables size of interconnection system, while the transmission system cost was not considered. Hou et al. in [13] utilized an Adaptive Particle Swarm Optimization (APSO) algorithm. The optimal interconnection layout and the location of OS are simultaneously found by using an APSO-MST algorithm. However, the shipping and burying costs of subsea cables as well as the total power losses were not considered. In [14], the authors found the optimal electrical interconnection and transmission systems of an OWF by APSO-MST algorithm and C-means clustering method. Nevertheless, for this discrete optimization problem, adjusting real values to integers in APSO algorithm may not be the best choice. Similar APSO-MST algorithm was adopted in [15] to develop their simultaneous optimization by considering wake effect and adding WTs location into the optimization problem. However, the comparison could not be fair, while the OWF project area was changing in the optimization process. In addition, for this complex and discrete optimization problem, adjusting real values to integers may decrease the performance of APSO algorithm. Furthermore, the edges with crossing potential are eliminated (similar to reference [11]), which may miss some feasible solutions.

In this paper, in order to minimize the investment and operating cost of an OWF, a new formulation is proposed to simultaneously find the optimal configuration and cables size of the interconnection and transmission systems as well as the rating (and thus costs) of other offshore components including MV and HV switchgears, OS platforms and transformers. The proposed formulation provides a useful tool that finds the optimal the electrical system layout of on- and off-shore wind farms (with some minor changes). In order to fill the research gaps, the significant contribution of this paper is incorporating the annual cost of energy losses into the objective function as an operating cost so that a multi-objective optimization problem is formed. In addition, no clustering method for Wind Turbines (WTs) is used to allow the proposed algorithm to automatically perform this task by itself. Furthermore, a new method is proposed to avoid appearance of any crossed edges in the optimal configuration without eliminating the feasible edges with crossing potential a priori.

The remainder of the paper is organized as follows. Section II describes the optimization problem. In section III, the case study is introduced. The results are illustrated and discussed in section IV. Finally, section V concludes the paper.

II. OPTIMIZATION PROBLEM

The optimization formulation aims to find the optimal layout of electrical interconnection and transmission systems. However, incorporating the cables costs into the objective function creates variable cost edges in each individual solution. Therefore, a complex, non-convex and non-linear discrete optimization problem is formed that needs to be solved by a metaheuristic algorithm.

Similar to this paper, reference [11] aimed to simultaneously find the optimal layout of the interconnection and transmission systems, and other offshore components (electric system layout optimization) of an OWF. However, in order to decrease the problem size, the WTs were clustered before being solved as individual MST problems, which may miss a global optimum solution. Their modeling of electrical grid was formulated based on an adjacency matrix that is solved by a binary GA.

In this paper, modeling for both interconnection and transmission systems are formulated based on the expansion of proposed formulation in [16]. However, a new multi-objective optimization is proposed by adding the annual cost of energy losses into the objective function. Moreover, the assumed cost functions for subsea cables are different from [16] but are considered to be identical to the ones in reference [11]. Similar to [16], the integration of all WTs is considered without any clustering method to allow WTs be clustered automatically according to the ampacity of cables, and crossing avoidance is considered by applying a penalty term. A k_i-based (integer-based) GA is utilized in this paper, where k_i is the number of choices in discrete decision set for i^{th} optimization variable. The selection and crossover methods are considered to be roulette wheel and multipoint with 2 to 4 random splice points, respectively. The population size and mutation probability are assumed to be $2\times(N+n_{OS})$ and 0.05 respectively, where N is the number of WTs and n_{OS} is the number of OSs.

A discrete decision set (B_i) is identified for each (i^{th}) individual WT. Note that, every WT has a chance to connect to an OS directly. B_i set consists of k_i feasible choices as follows:

$$B_i = \sum_{\substack{n=1 \\ n\neq i}}^{N+n_{OS}} \delta_{i,n} \cdot n \qquad \forall\ i \in \{1, 2, \dots, N\} \tag{1}$$

$$\text{s.t.} \sum_{n=1}^{N+n_{OS}} \delta_{i,n} = k_i \quad \forall\, \delta_{i,n} \in \{0,1\}$$

where, n is the node index (either OSs or WTs), i WT index, N the number of WTs, n_{OS} the number of OSs, k_i the number of choices in the decision set for i^{th} node, and $\delta_{i,n}$ is a binary variable {0, 1} that is assigned 1 if n^{th} node is a feasible choice, otherwise 0. The optimization variable for this problem is the index of the connected node to the i^{th} node that is assumed to be j, where this j^{th} index is chosen from B_i set for i^{th} node (among k_i available choices).

Figure 2 provides the optimization flowchart of our GA-based algorithm. Cable crossing, looping and overloading are the penalty terms that applied in this optimization process, once any of these penalty terms flagged during the process, the solution is eliminated. The most important and challenging penalty term is the cable crossing. Actually, a novel method is proposed in this paper, which lets both potential crossed edges (branches) to have chance to be selected individually. At first, the joint of every two-edges that have crossing potential are detected and stored in a set. Then, in every solution, crossed cabled can be easily detected, once any element of this set appears together.

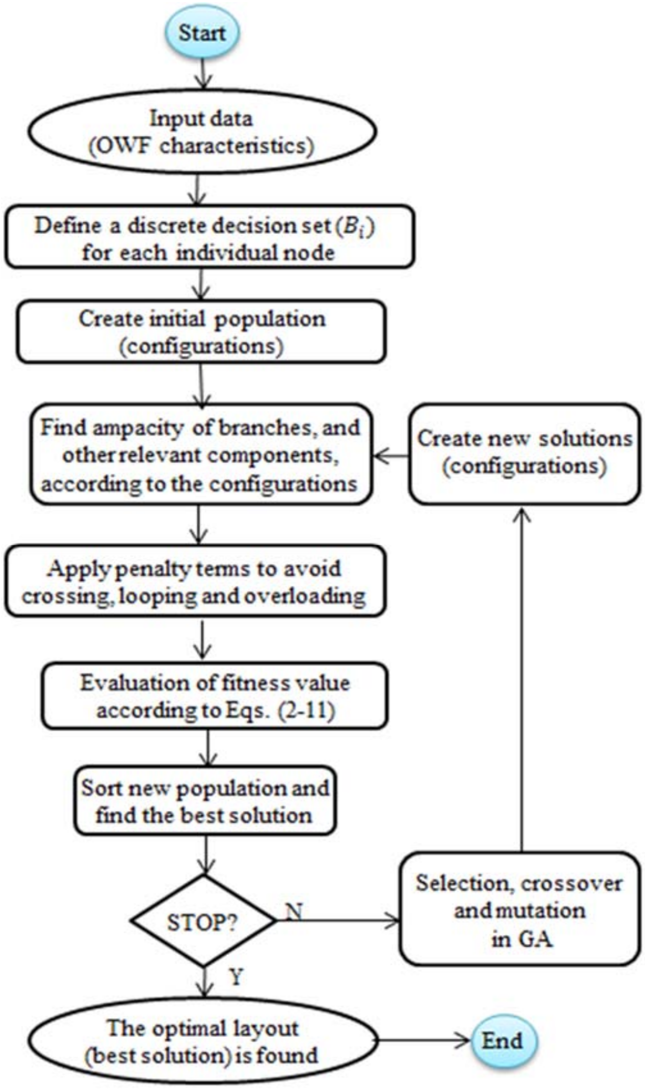

Fig. 2: Flowchart of the optimization algorithm

The following objective function is used to minimize the summation of the total investment cost for all components of OWF electrical system (C_{inv}) and the annual cost of electrical energy losses (C_{loss}):

$$\min \{\boldsymbol{C}_{\textbf{inv}} + \boldsymbol{C}_{\textbf{loss}}\} \tag{2}$$

In order to make a counterbalance between the total investment cost and the annual cost of energy losses (Eq. 10), the total investment cost is supposed to be made today and paid off during of OWF lifetime as follows:

$$C_{\text{inv}} = \frac{r.LT.(1+r)^{LT}}{(1+r)^{LT}-1} \times \frac{1}{1-PR} \times \left(C_{\text{MV}} + C_{\text{HV}} + C_{\text{pl}} + C_{\text{tr}} + C_{\text{sw}}\right) \tag{3}$$

where, r is the interest rate (4%), PR the annual profit (2%), LT OWF lifetime (20 years), C_{MV} and C_{HV} are the initial invest for MV and HV cables respectively, C_{pl} is the initial invest for the OS platforms, C_{tr} the initial invest for HV transformers on the OSs, and C_{sw} is the sum of initial invest for MV and HV switchgears. The costs of MV and HV switchgears are assumed to be M\$0.473 and M\$0.53 respectively (same as [11]), thus the MV and HV bay can be easily found according to the total number of feeders.

In order to find the total cables cost and the total costs of shipping and burying procedure for subsea cables, the following formulation is utilized similar to [16]. However, the OSs are additionally considered as extra nodes in this paper, making the length of chromosome (number of variables) to be $N+n_{\text{OS}}$. The $C_{\textbf{MV}}$ (and similarly $C_{\textbf{HV}}$) can be found as follows:

$$C_{\textbf{MV}} = \sum_{i=1}^{N} D_{\boldsymbol{i},\boldsymbol{j}} \times \left(Csb + \sum_{d=1}^{m} \lambda_i(a_{\boldsymbol{d}}) \cdot cc_{\textbf{MV}}(a_{\boldsymbol{d}}) \right) \tag{4}$$

$$\text{s.t.} \sum\nolimits_{d=1}^{m} \lambda_i(a_{\boldsymbol{d}}) = 1 \quad \forall\, \lambda_{\boldsymbol{i}} \in \{0,1\},\ a_d \in A$$

where, $D_{\boldsymbol{i},\boldsymbol{j}}$ is the distance [m] between nodes i and j that can be calculated by Eq. (7), j the index of the next connected node to the i^{th} WT that chosen from B_i set, N the number of WTs, Csb the sum of shipping and burying costs that is assumed to be \$152/m for MV subsea cables as a constant value [11], [17], [18], m the number of available sizes in the subsea cable set, $a_{\boldsymbol{d}}$ the cross-sectional area of d^{th} size in the subsea cable set, $\lambda_{\boldsymbol{i}}(a_{\boldsymbol{d}})$ a binary variable {0 , 1} in order to assign the required cable size (d^{th} size) according to the current flowing between WTs ($I_{i,j}$) as defined in Eq. (5), and $cc_{\textbf{MV}}(a_{\boldsymbol{d}})$ is the cost of the MV cable [SEK/km] with size of a_d, which is found by Eq. (6) [19]. Note that, in order to have a fair comparison, the exchange rates are also considered identical to [11] (1 SEK= €0.1155 and \$1 = €0.7694). Moreover, in order to minimize the fault probability of buried subsea cables, the cables size are designed so that all WTs generate the full power rating (the worst scenario), thus the uncertainty of wind profile in OWF area is not considered in this paper.

$$\begin{cases} \lambda_i(a_d) = 1 & if \quad I_{\max}(a_{d-1}) < I_{i,j} \le I_{\max}(a_d) \\ \lambda_i(a_d) = 0 & if \quad otherwise \end{cases} \tag{5}$$

$$cc_{\textbf{MV}}(a_{\boldsymbol{d}}) = A_p + B_p.\exp\left(C_p \times 10^{-8}.S_{\max}(a_{\boldsymbol{d}})\right) \tag{6}$$

where, A_{p}, B_{p} and C_{p} the constant cost factor of AC cables according to the rated voltage of cables that are given in Table 1~~Table 1~~, and $S_{\max}(a_{\boldsymbol{d}})$ is the maximum permitted power [W] of the AC cables with size of a_d as follows:

$$S_{\max}(a_d) = \sqrt{3}\, U_{rated}.I_{\max}(a_d) \tag{7}$$

$$D_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{8}$$

where, (x_i, y_i) and (x_j, y_j) are the location coordinates of nodes i and j (the index of the chosen connected node), respectively.

Note that, the Eqs. (4) and (6) are also valid for $C_{\textbf{HV}}$ and $cc_{\textbf{HV}}(a_{\boldsymbol{d}})$ respectively, according to the rated voltage of HV system and the corresponding values from Eq. (7) and Table 1~~Table 1~~.

Table 1: Cost factor for different voltages of AC cables [19]

Voltage Level	*Ap*	*Bp*	*Cp*
33 kV	0.411×10^{6}	0.596×10^{6}	4.1
220 kV	3.181×10^{6}	0.11×10^{6}	1.16

The estimated costs of the OS platforms (C_{Pl}) and OS transformers (C_{Tr}) are taken from [20], [21] as follows:

$$C_{\text{Pl}} = 2.14 + 0.0747\,.\,S_{\text{Tr,max}} \tag{9}$$

$$C_{\text{Tr}} = 0.03327\,.\,S_{\text{Tr,max}}{}^{0.7513} \tag{10}$$

where, C_P and C_T are the cost [Euro] of the OS platforms and OS transformers respectively, and $S_{Tr,max}$ is the power rating [VA] of the OS transformer. The decision set to select suitable transformer are as follows:

S_{Tr} [MVA] = {150, 180, 200, 250, 300, 400, 630, 722, 800}

In this paper, since the WTs generated current are considered to be as much as the WTs power rating (the worst scenario), the annual cost of approximate energy losses (C_{loss}) is calculated according to the square rate of OWF capacity factor as below:

$$C_{\text{loss}} = 8760 \times LCoE \times CF^2 \times \sum_{i=1}^{N} \Delta P_i \qquad (11)$$

where, $LCoE$ is the levelized cost of energy [\$/MWh] for OWFs (\$140/MWh), CF the capacity factor [per unit] of OWFs (assumed to be 0.45) [22]. ΔP_i is the active power losses of the connected branch to i^{th} WT [MW] in the worst case that is calculated as follows:

$$\Delta P_i = 3 \cdot R_i(a_d) \cdot {I_{i,j}}^2 \cdot D_{i,j} \qquad (12)$$

where, $R_i(a_d)$ is the AC resistance [Ω/m] of the assigned cable size (a_d) at 90ºC, and $I_{i,j}$ is the current flowing from node i to j.

III. Case Study

In this paper, a real OWF called "Saint-Nazaire" in Herare Province of France is considered which has not been built yet, as it still subjects to some design changes. It consists of 80 WTs with power rating of 6 MW each. In order to minimize wake effect [23], the spacing in each direction is considered to be 7×D (about 1 km), where D is the diameter of the WT blades. The WTs topology is shown in Fig. 3~~Fig. 3~~, where the location coordinates of the Onshore Connection Point (OCP) is assumed to be {−20, −20}. Detailed data of the OWF is available in reference [24].

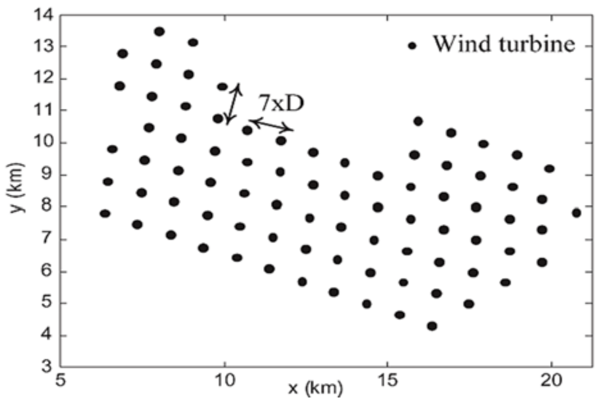

Fig. 3: The WTs topology of the studied OWF [11]

In order to demonstrate the effectiveness of the proposed optimization algorithm, the optimal layout of electric system of this OWF is found, and compared with another study [11] that has utilized the same OWF case study. In order to have a fair comparison the following assumptions and constraints are considered in this paper, identical to [11].

- The location and power rating of WTs are fixed.
- Only HVAC solution is considered for transmission system.
- Fixed voltage is considered for both MV and HV sides.
- Due to very low probability fault for buried subsea cables (about 0.001/km/year) [25], Loop design configuration is not considered, and thus the electric system reliability of OWF is not taken into the account.
- No parallel MV subsea cable is considered between WTs, however parallel HVAC lines might be required.
- The transmission system utilizes 220 kV subsea cables, and sizes of 800 and 1000 mm^2 are available in decision set.
- Two OSs are considered to gather the generated power of WTs, where only one OCP is considered in the optimization.
- Three-core subsea MV cables (33kV) are utilized for interconnection system, while minimum and maximum sizes are considered to be 120 mm^2 and 800 mm^2 respectively (same as [11]). Thereby, according to the nominal ampacity of each WT five subsea cables size are assigned (120, 240, 300, 500 and 800 mm^2).

Note that, as explained in previous section, identical to [11] a constant Csb is considered in the objective function for every chosen branch. However, by providing required data from sea bed geology and soil conditions, different Csb values can be easily considered into the objective function of our proposed formulation. Because, the Csb and/or the cables trenching length of some feasible branched may incense compare to the direct distance. Hence, similar to the $D_{i,j}$, individual shipping and burying costs ($Csb_{i,j}$) could also be assigned for every chosen branch.

IV. Results and Discussion

The obtained optimal results of our formulation and that of reference [11] are given in Table 2~~Table 2~~. The optimal configurations and cables size of both studies are depicted in Fig. 4~~Fig. 4~~ and Fig. 5~~Fig. 5~~, respectively.

Table 2: The optimization results of both studies

The parameters	The optimal values of our proposed formulation	The optimal values in reference [11]
Cost of interconnection system	M€44.509	M€45.559
Cost of transmission lines	M€97.638	M€97.638
Cost of offshore transformers	M€6.327	M€6.327
Cost of OS platforms	M€62.514	M€62.514
Cost of MV switchgears	M€7.112	M€7.112
Cost of HV switchgears	M€2.449	M€2.449
Total investment cost (C_{invest})	M€220.50	M€221.60
Total length of MV cables	82.718 km	83.40 km
Total length of HV cables	84.92 km	84.92 km
No. of MV feeders per OS	{7,6}	{6,7}
Size of 3-phase HV cables	800 mm^2 per OS	800 mm^2 per OS
Transformer power, per OS	{250, 250} MVA	{250, 250} MVA
Interconnection system power loss	2.869 MW	3.084 MW
Cost of interconnection energy loss	M€0.55	M€0.589
Overall cost of OWF	M€221.05	M€222.19

Electric system		

By comparing two columns of Table 2~~Table 2~~, it can be noticed that the proposed formulation in this paper improves the optimization results in interconnections system. However, the investment cost of transmission system and offshore components are turned out to be same as [11], due to limited search space of their optimization.

In addition, since the power losses was not included in objective function in [11], the total power losses and the annual cost of energy losses were higher in their optimal results compared to our optimal results in this paper. Hence, the overall cost of entire electric system layout of OWF in this paper was reduced by M€1.14. In fact, the total cost of interconnection system is decreased by 2.5% in this paper. The improved optimal electric layout that has led to a decrease in the total power losses can be also revealed visually by comparing the optimal configurations in Fig. 4~~Fig. 4~~ and Fig. 5~~Fig. 5~~. For instance, the cable connection (edge) that is located at the Cartesian coordinates of {7.5, 12.5} or {14.5, 8} in Fig. 5~~Fig. 5~~ (highlighted lines) could be replaced by another possible cable connection such as {7.5, 11.5} or

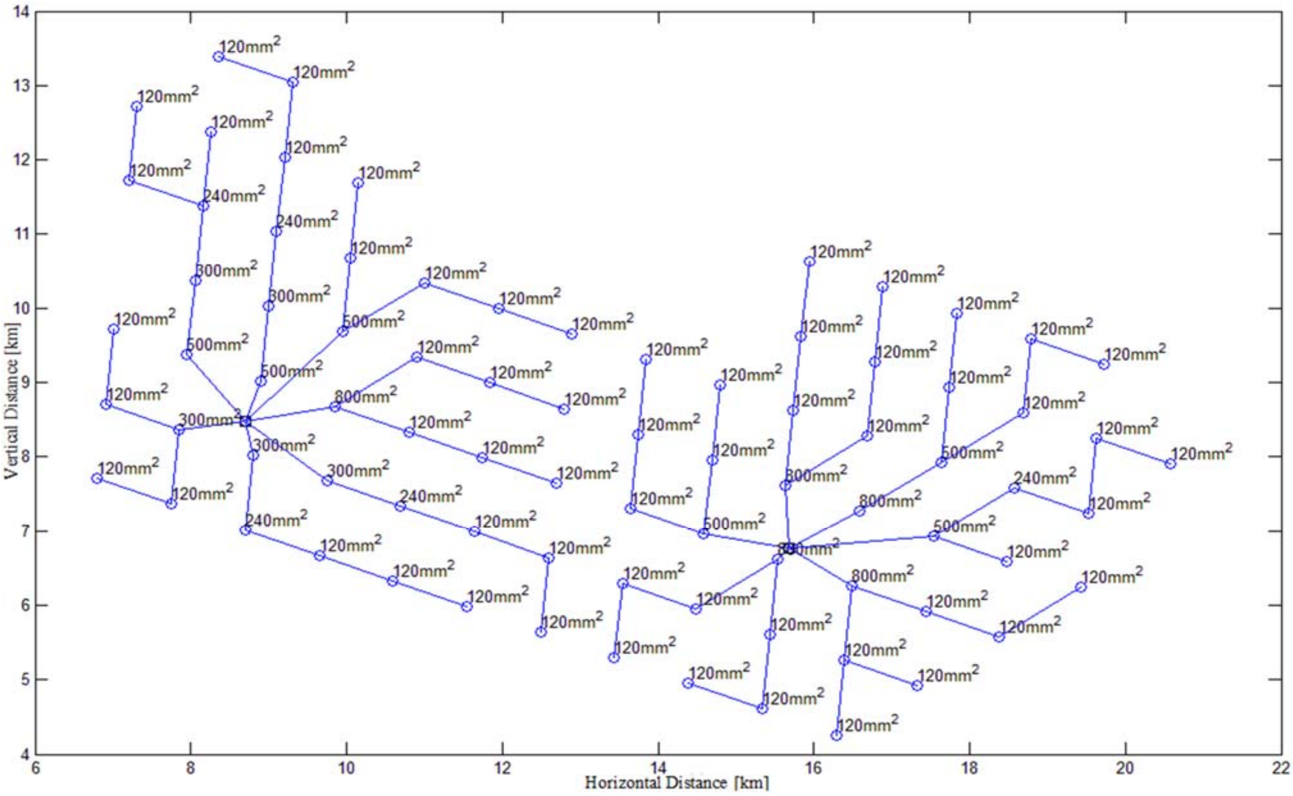

Fig. 4: The optimal electrical interconnection layout with our proposed formulation

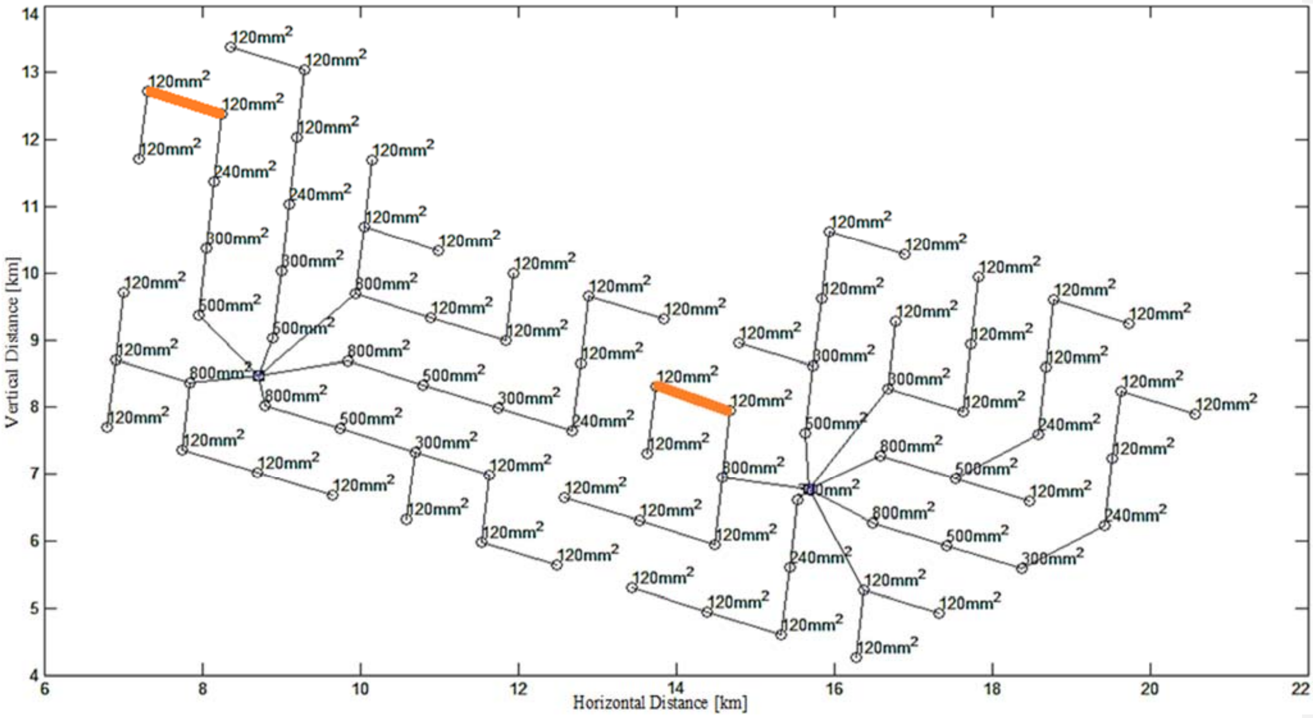

Fig. 5: The optimal electrical interconnection layout in [11]

{14.5, 7} so that the total power losses is decreased without changing the total investment cost.

V. Conclusions

This paper proposes an optimization formulation to minimize the total investment and operating cost of the electrical connection system of a real case OWF. In this paper, an optimization problem is formulated that simultaneously optimizes the electrical configuration and cables size of interconnection and transmission systems as well as offshore components such as HV and MV switchgears, OS platforms and transformers. In addition, the annual cost of electrical power losses is included in the objective function besides the total investment cost, thus a multi-objective optimization problem is created. This complex discrete optimization problem has been solved with an integer-based GA. Furthermore, in order to depict the improvements of our proposed optimization formulation, the obtained optimal results are compared with another study, considering the same OWF with identical assumptions and constraints. The optimal results reveal that the total cost of the interconnection system is decreased by 2.5%. However, the other optimal results are found rather the same, as the optimization problem for transmission system was a simple optimization problem with small search space.

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