Optimal Electric Network Design for a Large Offshore Wind Farm Based on a Modified Genetic Algorithm Approach

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***Abstract*—The increasing development of large-scale offshore wind farms around the world has caused many new technical and economic challenges to emerge. The capital cost of the electrical network that supports a large offshore wind farm constitutes a significant proportion of the total cost of the wind farm. Thus, finding the optimal design of this electrical network is an important task, a task that is addressed in this paper. A cost model has been developed that includes a more realistic treatment of the cost of transformers, transformer substations, and cables. These improvements make this cost model more detailed than others that are currently in use. A novel solution algorithm is used. This algorithm is based on an improved genetic algorithm and includes a specific algorithm that considers different cable cross sections when designing the radial arrays. The proposed approach is tested with a large offshore wind farm; this testing has shown that the proposed algorithm produces valid optimal electrical network designs.**

***Index Terms*—Electric distribution system, genetic algorithm, offshore wind farm, optimization.**

I. Introduction

WIND ENERGY is gaining increasing strategic and economic importance throughout the world. It is one of the more promising options amongst the various renewable energy generation technologies and is expected to play a significant role in reducing the environmental implications of meeting modern societies demand for electrical power. The use of offshore wind power generation is attractive for the following reasons: 1) offshore wind farms will not take up valuable land resources; 2) the use offshore locations will mean that the wind farm will have minimal landscape and visual impact and will not produce noise pollution; 3) wind flow will not be perturbed by structures or forests, thereby the winds striking the turbine blades will be stronger and steadier causing an increase in the performance of the turbine; 4) offshore wind turbine designs with larger single unit rated power than onshore designs are available, these larger ratings allow improved economies of scale; and 5) sea water affords an opportunity for accessible and low cost component cooling.

Large-scale offshore wind farms are being developed all around the world. This is particularly true in European countries bordering the North Sea where significant offshore wind resources exist in the shallow coastal waters. Despite this development offshore wind farm technologies are not as mature as their onshore brethren and the cost of an offshore wind farm is higher than that of an onshore wind farm of equivalent size

A large offshore wind farm may consist of hundreds of individual wind turbine (WT) generators connected to a medium voltage network, or collector system, that is itself connected to the transmission system at the point of interconnection (POI). The local WT collection system begins with the transformers that are installed at every wind turbine, usually in the base of the tower. These transformers step the voltage up from the generation voltage, typically 690 V, to the medium voltage (typically 25–40 kV [1]) used by the distribution system that the WTs are connected to. This medium voltage (MV) distribution system will consist of one or more *feeders* and these feeders are connected to offshore transformer substations that collect the electricity produced by the WTs connected to the feeders.

Offshore wind farms typically consist of several transformer substations that collect the electricity produced by the wind farm, an integration system is then used to transmit the energy from all of these individual substations to the central or terminal substation, which steps the voltage up to a transmission voltage of 130–150 kV, the highest voltages currently in use for ac submarine cables [1]. The distance between the terminal substation and the POI typically ranges from ten kilometers to hundreds of kilometers, for this reason a high voltage transmission system is needed (see Fig. 1).

Developing wind power applications in offshore environments is challenging for the following reasons: 1) offshore wind farm locations are always at least 10 or 20 km away from land and at this distance from the shore the water depths encountered are between 10 and 20 m; 2) large offshore wind farms may require several on-site sea substations to collect the wind turbine generation and transmit it to the onshore system; and 3) offshore wind farms require specialized equipment

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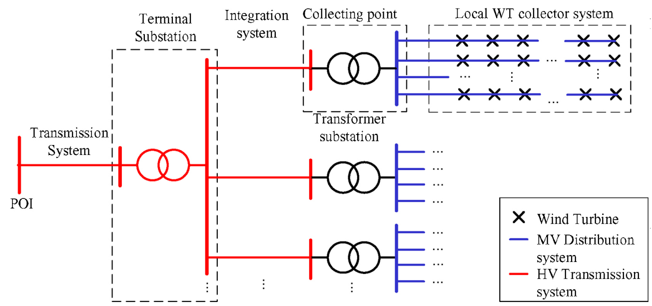

Fig. 1. Electrical network for a large wind farm.

for their construction and maintenance and this dramatically increases the cost of the wind farm when compared to onshore equivalents.

The design of local WT collection, integration and transmission systems for an offshore wind farm (see Fig. 1), including topology and component selection, should be carefully specified to reach the necessary balance between technical performance and economic cost. The investment necessary for an offshore wind farm distribution system is almost three times that necessary for an onshore wind farm [2].

Optimization of the design of the offshore electrical network therefore offers an opportunity to achieve a remarkable reduction in the total cost of an offshore wind farm. The number of variables involved in this problem and the optimal solution require the use of computational optimization.

Various layouts of wind farms considering both ac and dc have been investigated in [3] and [4], and inventory of electrical system used in wind parks has been presented in [5]. There are a lot of publications about wind farm design [6]–[9]. The unique technical and economic challenges involved on the design of collection and transmission system for offshore wind farms have been discussed in some publications [4], [10]–[12]. Zhao *et al.* [13]–[15] used the GA approach to solve the configuration of the wind farm and analyze the behavior of the GA in [16]. Hausler *et al.* [17] investigated the layout of various wind parks (using both ac and dc). Optimization of electrical connection schemes for offshore wind farms considering solely investment cost models is resolved using GA in [18]. Nandingam *et al.* [19] used geometric programming to solve an optimization model based on cost, loss, and reliability, for a single main substation and this approach has been tested using a small wind farm. Several publications are focused on the reliability problem of the collector systems [20]–[22]. The standard GA is improved with immune algorithm in [2] and the cost model of investment and operation are included; however, this approach could be improved by considering different cable cross sections in the design of local WT collection system.

In this paper, a novel approach to solving the problem of optimal electric network design for large offshore wind farms is presented. It is based on improved GA and includes a new approach based on a modified approach of the traveling salesman problem (TSP), it has been used for designing the radial arrays, furthermore, the cost model has been improved by including more realistic terms. The optimization model and the solution algorithm proposed are shown in Sections II and III, respectively. Section IV presents the results of the evaluation of one study case. The case considered is a large offshore wind farm that consists of 280 wind turbines.

II. Optimization Model

The optimal design of the electrical network supporting an offshore wind farm is dependent on the following: 1) the number of offshore transformer substations; 2) the capacity and location of each substation; 3) the topology of the local WT collection and the integration system; and 4) satisfying any technical restrictions and minimizing the total cost.

In this section, an optimization model which is suitable to find the optimum local WT collection system of an offshore wind farm is described. This model determines the approach that allows the WT to be connected to the offshore substation at the minimum cost whilst satisfying radial topology for feeders and other technical restrictions. The total investment cost (C_{total}) is calculated assuming that the whole investment is made in the first year and paid of during the life time of the wind farm. In addition, it is assumed that some profit shall be made.

The annual investment cost of the electric network design of an offshore wind farm is calculated as the sum of the annual investment cost for the MV cable (C_CB) and substations (C_{SS}) and the cost of the transformer installed at each WT (C_{WTT})

$$\begin{aligned} C_{\text{total}} &= C_{\text{CB}} + C_{\text{SS}} + C_{\text{WTT}} \\ &= \frac{r\,(1+r)^{N_{\text{lt}}}}{(1+r)^{N_{\text{lt}}}} \frac{100}{100 - PR} C_{\text{inv}} = K C_{\text{inv}} \end{aligned} \tag{1}$$

where N_{lt} is the wind farm life time, r is the interest rate, PR is the profit in percent, C_{inv} is the total investment cost necessary for the wind farm electrical system, and K is a constant.

The optimization problem can be described as follows:

$$\begin{aligned} &\min\,[C_{\text{Total}}] \\ &\min\left[K\left(\sum_{j=1}^{N_{\text{ss}}}\sum_{i=1}^{N_{\text{Fi}}} C\left(F_{j,i}\right) + \sum_{i=1}^{N_{\text{ss}}} C(SS_i) + C_{\text{WTT}}\right)\right] \end{aligned} \tag{2}$$

subject to

$$\begin{aligned} &I_{\text{Lm}} < I_{\text{rated}}\,(c_m)\,, \qquad \forall m \in F_{j,i} \\ &\sum_{m\in F_{j,i}} |\Delta V_m| > \Delta V_{\min}, \qquad i = 1, \\ &\ldots, N_{WTi}, \; j = 1 \\ &\ldots, N_{\text{ss}} \\ &X_i \bigcap_{\substack{i,\,j\,\in\,X \\ i \neq j}} X_j = \emptyset \\ &X_i \bigcup_{i \neq j} X_j = X \end{aligned} \tag{3}$$

where N_{ss} is the number of substations, N_{Fi} is the number of feeders on the ith substation, $C(F_{j,i})$ is the total investment cost of the jth feeder on the ith substation ($F_{j,i}$), $C_{SS,i}$ is the total cost of investment of the ith substation, and C_{WT} is the total investment cost of the step-up transformers connected to the WT. I_{Lm} is the nominal current in the mth section of the feeder F_{ij}, and $I_{\text{rated}}(c_m)$ is the rated current for the c_m type of conductor. X_j is a set whose elements defining the elements connection belonging to the j group. $\mathbf{X}$ is a vector containing the sets of connections definitions for all elements involved in the electric network for the offshore wind farm.

A. Cost Model

1) *Transformer Connected to WT:* The cost model for the step up transformers at each wind turbine (C_{WTT}) is described as follows:

$$C_{\text{WTT}} = N_{\text{WT}} C_{\text{WT}} \tag{4}$$

where C_{WT} is cost of the transformer (see the Appendix) and N_{WT} is the number of wind turbine in the wind farm.

2) *Offshore Transformer Substation:* The total cost of the ith offshore transformer substation, $C(SS_i)$, can described as follows:

$$C\left(SS_i\right) = C_{HV,i}N_{HV,i} + C_{MV,i}N_{MV,i} + C\left(ST_i\right)N_{Tr,i} + C_{R,i} + C_{C,i} \tag{5}$$

where $C_{HV,i}$ and $C_{MV,i}$ are the cost of one substation bay at the necessary high voltage and medium voltage level, respectively. $N_{HV,i}$ and N_{MVi} are the numbers of HV and MV bays, respectively, and $N_{Tr,i}$ is the number of transformers in the substation.

The cost of the step-up transformer installed in the ith substation $C(ST_i)$ depends on the rated power and voltage levels. For transformers with rated power range of 6.3–150 MVA and high voltage side ratings in the range 47 to 140 kV and low voltage side of the range 25–40 kV [19], [23] the cost is determined as function of rated power (S_{STrated}) by

$$C\left(ST_i\right) = \alpha_1 + \alpha_2 S_{\text{STrated}}^{\beta_1} \tag{6}$$

where α_1 is an offset constant equal to -0.205×10^6, α_2 is a slope constant equal to 364.6, and the exponent β_1 is 0.4473.

$C_{R,i}$ is the cost of the other devices necessary in a substation such as protection relays and station control equipment. The construction cost for the substation ($C_{C,i}$) is defined considering the equivalent area of construction area for the transformer as well as the high and medium voltage bays and the unit price of construction.

3) *Undersea Cables:* The number of WT connected to the ith radial feeder of the collecting system (N_{Fi}) depends on the maximum power that can be transmitted by the undersea cable whilst satisfying certain power quality constraints. The necessary current carrying capacity in one radial configuration will vary between different sections of the feeder and thus using different cross sections of cable will reduce the cost without compromising performance.

Fig. 2 shows the configuration of ith feeder ($F_{j,i}$), each wind turbine injects current (I_{WTm}) into the feeder, the cable size c_m for each section carrying I_{Lm} current are depicted from the point of connection at the jth offshore transformer substation ($\text{PCC}_{j,i}$). The cable sizes (c_m) are based on the criteria: the load current and the maximum voltage drop permissible, considering the correspondent length in each section (d_m).

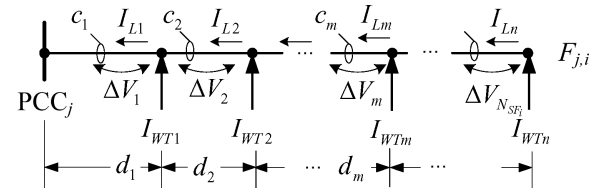

Fig. 2. Single line diagram of the ith feeder of jth offshore transformer substation.

The cost of the ith feeder ($C_{Fj,i}$) at the jth offshore transformer substation can be obtained as follows:

$$\text{C}_{Fj,i} = C_{SMj,i} + C_{CbSj,i} \tag{7}$$

where C_{SMJ}, i is the shipping and installation cost for the undersea cables in the feeder and $C_{CbS,i}$ is the total cost of the MV cables

$$\text{C}_{CbSj,i} = \sum_{m=1}^{N_{SF_i}} C_{CB}\left(c_m\right) L_m \tag{8}$$

where C_{CB} is the cost of the c_m type of conductor used in the section mth, L_m is the length of section mth, and N_{SFi} is the number of cable segments in the ith feeder.

The cost of the MV cables used in the local WT collection system is a function of conductor area $A(c_m)$ and the rated voltage (V_{rated})

$$\begin{aligned} C_{\text{CB}}\left(c_m\right) &= \alpha_3 + \alpha_4 e^{\frac{\beta_2 S_{\text{rated},m}}{10^8}} \\ S_{\text{rated},m} &= \sqrt{3} V_{\text{rated},m} I_{\text{rated}}\left(c_m\right) \end{aligned} \tag{9}$$

where C_{BC} is the cost of the cable c_m, $I_{\text{rated}}(c_m)$ is the rated current for the c_m type of conductor, α_3 is an offset constant, α_4 is a slope constant and the exponent β_2 (values of this parameters are shown in the Appendix), and $S_{\text{rated},m}$ is the rated power of the cable.

III. Optimization Method

A real offshore wind farm may have hundreds of wind turbines, which are geographically spread out in the range of several to tens kilometers, there are many feasible schemes for the electrical network design.

The optimization problem of the network design for an offshore wind farm involves two main aspects: 1) integration of the interconnection of the offshore transformer substation, and 2) the local WT collection system. The solution of the optimization problem defines the position of substations (transformers and terminal), the connection between the substations and the topological connection between the WTs and the substations (feeders). There are many possible configurations for the electrical network of one offshore wind farm; it is a NP-hard problem in combinatorial optimization and is suitable for intelligent heuristic methods [24].

GA has demonstrated special efficacy when searching and optimizing problems that have huge solution spaces with discrete variables; the optimal design of an offshore wind farm layout is such a problem [18]. In this paper, the efficiency of the GA is improved considering the specific case designed specially for radial topology in the local WT collector system. For this propose, the GA is combined with the solution approach used to solve the classical multiple traveling salesman problem (mTSP). This approach solves the problem of designing a local WT collector, considering multiple radial feeders connected to the PCC, and is called the *open-multiple traveling salesmen problem* (omTSP). A special gene coding developed for this specific formulation is presented in this section too.

A. General Description of the omTSP

The mTSP can, in general, be defined as follows. Given a set of n nodes (cities), let there be m salesmen located at a single node. The remaining nodes that are to be visited are called intermediate nodes. In this paper, the TSP is modified into the so-called fixed-start and open-multiple traveling salesmen problem (omTSP). This consists of finding tours for all m salesmen, such that all salesman starts its own travel from one fixed-location city, travels to a unique set of cities (none of them close their loops) without returning to the starting location. Except for the first city (common starting point), each city is visited by exactly one salesman.

The mathematical definition of the problem starts from graph theory. Let graph $G = (V, E)$, a weighted undirected graph with cost matrix C, where V is the set of n nodes (vertices) $\{1, 2, ..n\}$, and E is the set of arcs (edges). The omTSP consists of finding a set of m sub-graphs $G_1(V_1, E_1)$, $G_2(V_2,E_2)$, $\ldots$, $G_M(V_m, E_m)$ that satisfy

$$V_i \bigcap_{i \neq j} V_j = v_1 \qquad i, j = 1, 2, \ldots, m \tag{10}$$

$$E_i \bigcap_{i \neq j} E_j = \emptyset \qquad i, j = 1, 2, \ldots, m. \tag{11}$$

Cost on edge $e = \{v_i, v_j\}$ are $c(e) = c_{ij} = c_{ji}$. All costs are positive. The cost metric can be defined in terms of distance, time, and so on. Although the TSP has received a great deal of attention, the research on the mTSP is limited [25], [26] and on the omTSP the lack of research is larger.

B. OmTSP Model for the Electric Network Design Problem

To convert the omTSP into the problem of the optimal large find farm electric network design, consider n nodes (vertices) and m salesman, which may be viewed as N_{WT} wind turbines plus the N_{ss} substations ($n = N_{\mathrm{WT}} + N_{\mathrm{ss}}$) and m feeders in the local WT collector system of each transformer substation. Mathematical explanation of the problem conversion may be explained for one transformer substation "without loss of generality."

Let $F_\pi = \{F_{\pi(1)}, F_{\pi(2)}, \ldots, F_{\pi(m)}\}$ be a set of all feeders $F_{\pi(\mathrm{i})}$, where all vertices are visited exactly once (one per WT) and the starting point in common PCC (v_1)

$$F_\pi = V_{\pi(1)}, V_{\pi(2)}, \ldots V_{\pi(m-1)}, V_{\pi(m)}$$

$$V_{\pi(i)} \bigcap_{\forall i,j} V_{\pi(j)} = v_1 \qquad V_{\pi(i)} \bigcup_{\forall i,j} V_{\pi(j)} = V. \tag{12}$$

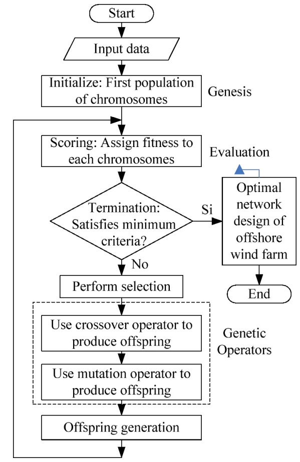

Fig. 3. Flowchart of the optimization approach.

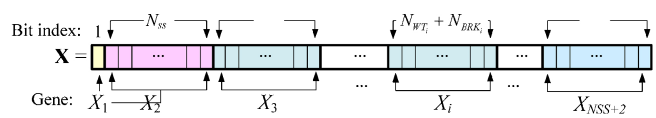

Fig. 4. Coding of chromosome **X**.

The cost of the feeder $C(F_{\pi(i)})$ is the sum of the cost of the conductor size used to walk the feeder $C_\pi(e_{\pi(\mathrm{i})})$

$$C_{Fi} = C\left(F_{\pi(i)}\right) = \sum_{j \in V_{\pi(i)}} C_\pi \left(e_{\pi(i)}\right). \tag{13}$$

The cost of this collector system $C(F_\pi)$ is the sum of the cost of the each feeder

$$C\left(F_\pi\right) = \sum_{j \in F_\pi}^{m} C\left(F_{\pi(i)}\right). \tag{14}$$

The output is the set of feeders F together its cost $C(F)$ in the feeder of minimum cost, OPT

$$\forall F_\pi : OPT = C\left(F\right) \leq C\left(F_\pi\right). \tag{15}$$

Note that this set of feeders is not necessary unique.

C. Genetic Algorithm for the omTSP

The efficiency of the GA can be improved for the specific case of this problem based on: consider radial topology on the local WT collector system and GA is combined with the solution approach used to solve the classical omTSP.

The main input data of the optimization problem is the coordinates (x_i, y_j) of the N_{WT} WT and N_{SS} the transformer substations, which is determined by micro-sitting assessment, this is then not part of the optimization problem.

The flowchart of the optimization approach is shown in Fig. 3, and it is drawn under the following general subsections.

D. Variables and Chromosome: Encoding

Coding all potential solutions to the chromosomes is the first step to solving the optimization problem [27], [28]; the chromosome **X** represents all electrical connection schemes and its characteristics (Fig. 4) defined by each gene (X_i).

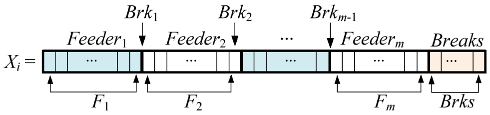

Fig. 5. Coding of gene X_i.

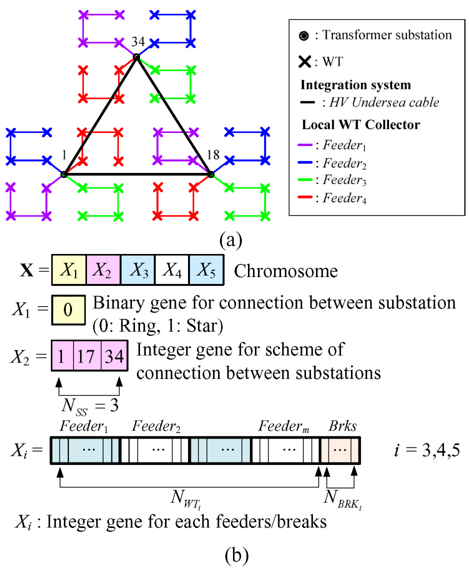

Fig. 6. Demonstrative example of the coding of chromosome **X**. (a) Electrical network design. (b) Coding of chromosome **X**.

The first gene X_1 in the chromosome defines the type of the connection in the integration system between the offshore substations (it is a binary representation, 1: star, 0: ring), the genes X_2 define the pattern of connection between the N_{ss} transformer substations, and the following genes X_i ($i = 3, .., N_{ss} + 2$) represent the connection topology of the feeders between N_{WTi} WTs and PCC for N_{Fi} feeders of i transformer substation (it is a integer coding) (see Fig 5). The number of breaks (N_{BRKi}) is given as follows:

$$N_{BRKi} = N_{Fi} - 1. \tag{16}$$

The coding used for the electric network design is illustrated with an example which consists of $N_{\mathrm{WT}} = 482\,\mathrm{MW}$ wind turbines and $N_{SS} = 3$ substations as shown in Fig. 6.

Four feeders ($N_{F1} = 4$) are used on the offshore transformer substation to collect the power produced by $N_{WT1} = 16\,\mathrm{WTs}$, then $n = 17$. Equal number of wind turbines ($N_{WT1}/N_{F1} = 4$) has been assumed in each feeder. A possible feeder/break combination might be as follows:

$$F_\pi = \{7, 6, 2, 3, 8, 4, 5, 9, 11, 10, 14, 15, 12, 13, 17, 16\}$$
$$Brks_\pi = \{4, 8, 12\}$$

where the point 1 represents the PCC in the transformer substation and 17 represents the location of the 16th WT [see Fig. 6(a)].

Fig. 7(a) shows the topology of the local WT collector system, the four feeders connected to the transformer substation 1. The power of the four WTs is clustered per each feeder, the collector system has been optimized in terms of: 1) the cables sizes to satisfy load current and minimize the

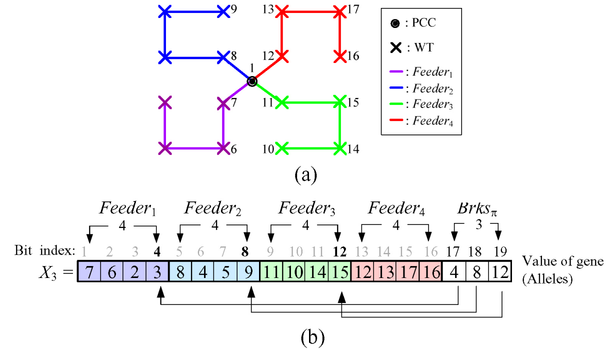

Fig. 7. Example of the encoding for the transformer substation 1 and X_3. (a) Feeders for transformer substation 1. (b) Coding of gene X_3.

voltage drop ($\Delta V_{\min}$) throughout the feeder, and 2) the pattern of connection between wind turbines has been optimized in order to minimize distances between them and the PCC.

The gene X contains the information (alleles) regarding the four wind turbines collected by each feeder $Feeder_1$, $Feeder_2$, $Feeder_3$, and $Feeder_4$, and the breakpoints inside the gene ($Brks$) in order to define the connectivity in the radial topology for every feeder [see Fig. 7(b)]. The $Feeder_1$ start from substation (point 1) and it connects the WTs numbered as 2, 3, 6, and 7. $Brks_1$ define the position inside of the gene (locus) where the feeders start and end, $Feeder_1$ ends at the locus 4, while $Feeders_2$ and $Feeder_3$ end at locus 8 and 12, respectively.

E. Initialization: Genesis

The origin of the evolution process is generating one random population of N_{pop} chromosomes which are suitable solutions for the problem. The first generation of genes for the feeders topology are created from random permutations of the numbered WT for possible route/break sequences.

F. Scoring: Fitness

During the evolution process the population is evaluated for each generation in order to select chromosome from the existing population and breed a new generation. The chromosomes are selected through a fitness-based process, where fitness is measured by a fitness function. The fitness function (F) used is the whole cost of the wind farm

$$F = C_{\mathrm{Total}}. \tag{17}$$

The chromosomes that represent solutions of lower cost have higher probability of evolving during this selection process.

G. Genetic Operator

Genetic operators (GO) are used in GA to maintain genetic diversity during the process of evolution, en-courage the recombination of excellent genes, and introduce new chromosomes. There are two GO in the proposed algorithm: *crossover* and *mutation*. They are applied separately for feeders and breaks into the genes used to represent feeder topologies. The GO mutation is used to randomly change the gene alleles.

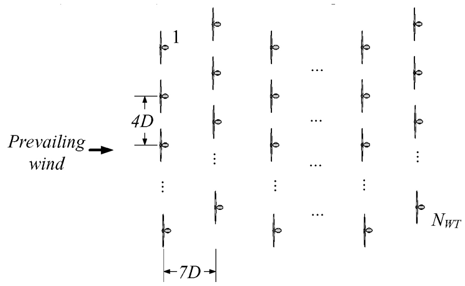

Fig. 8. Example of the encoding for the transformer substation 1 and X_3.

The purpose of the mutation GA is to prevent the genetic population from converging to a local minimum and to introduce to the population new possible solutions. The crossover operator is used in order to produce the next generation by combining the fittest individuals. Each pair of selected individuals produces a pair of new individuals for the next generation.

IV. Case Study

To demonstrate the capabilities and application of the approach presented in this paper for the optimal offshore wind electrical network design some numerical experiments are illustrated. Theoretical analysis over hypothetical wind farms then the solution of a practical optimization problem is presented.

All tests are performed considering 2 MW, $D = 80$ m diameter wind turbines. The local WT collection and integration system are designed using cross-linked polyethylene insulated undersea cables rated at 35 kV and 150 kV, respectively. The maximum voltage drop of 2% allowable is considered during the MV cable sizing and 1% for the HV integration system. The number of transformer in the substation is assumed one and the number of HV/MV bays are defined in each test case.

The optimization problem has been solved considering the life time of the wind farm considered in this paper will be 20 years, with an interest rate of 4% and profit of 3%.

In the following tests, the GA parameters are: population size is $(N_{\mathrm{WT}} + N_{\mathrm{ss}})^{0.5}$ individuals, the maximum generation is $200(N_{\mathrm{WT}} + N_{\mathrm{ss}})^{0.5}$ crossover probability is 0.8, mutation probability is 0.01.

The calculations were performed on a personal computer, which has a processor IINTEL Core 2 Duo CPU 2.10 GHz, RAM 4.0 GB, 64 bit-operating system.

A. Performance

A cluster of machines in a wind farm must be maintained certain spacing between the wind towers in order to optimize the power cropping. A regular array of wind turbine is used in the test wind farm. For simplicity in this paper, the test wind farms used for numerical simulations have tower spacing of 4-rotor-diameters along its rows and 7-diameter spacing between rows (4D×7D) as shown in Fig. 6.

The number of wind turbines has been increased and same proportion that number of feeders ($N_{Fi} = (N_{WTi})^{0.5}$), the number of substation is kept 4 in all cases. Table I shows a summary of the impact on the results for different cases considered. Fig. 8 shows the electric network design and best fitness function evolution for the test wind farm studied. Results show the collector system design with minimum cost may be the same solution of minimal feeder's length; however, it is not necessarily true in all cases, especially for wind farms with a large number of WT where several solutions satisfy the minimum cost.

Fig. 9 shows the optimal electric network design in two separated conditions: conductor distances and minimal total cost for Case IV, it is evident that the collector design for minimum cost does not coincide with the minimum distance. It is because of the increasing of the conductor size in those sections from the end of feeder to the PCC.

TABLE I

Summary of Results for Different Hypothetical Wind Farms

Case	N_{WT}	N_F	$C(F)$ Total Cost	Total Distance	Minimal Distance
I	36	3	3.458	3374.07	3374.07
II	64	4	4.868	6209.60	6209.60
III	100	5	9.987	10114.00	10114.00

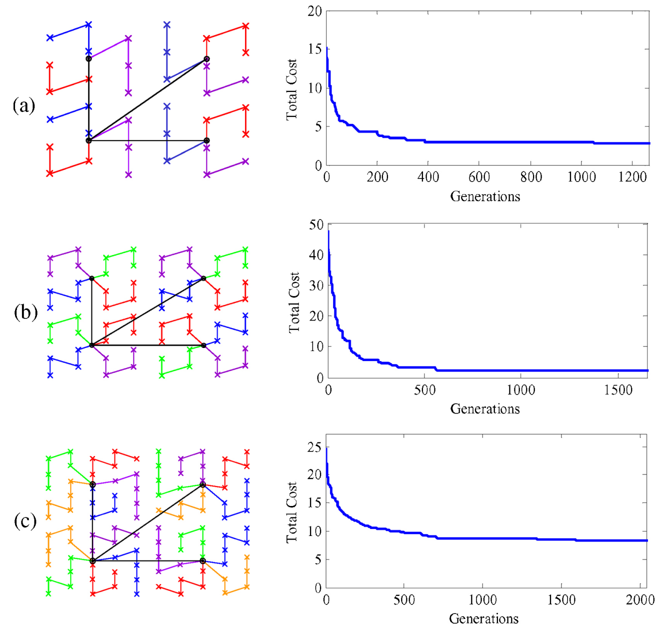

Fig. 9. Results of the different electric network design for the wind farm layout considered. (a) Case I, 1265 generations, performed in 4.2 min. (b) Case II, 1650 generations, performed in 8.2 min. (c) Case III, 2040 generations, performed in 10.2 min.

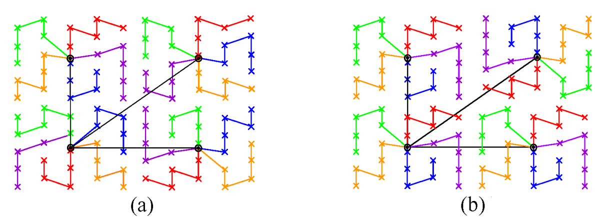

Fig. 10. Comparison between the optimal solution of electrical network design considering distances and cost. (a) Minimal distances. (b) Minimal cost. Case III.

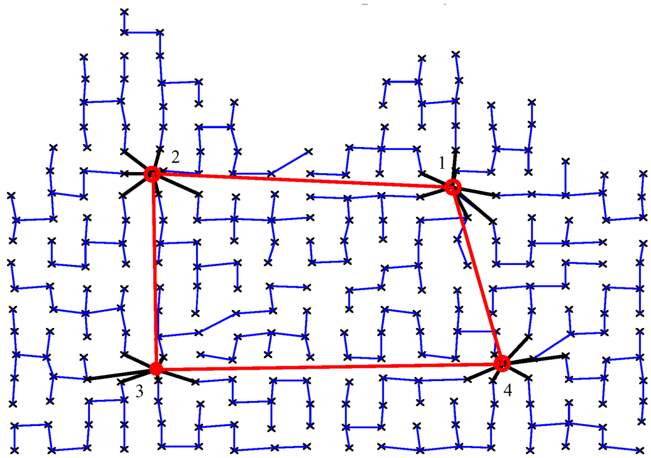

Fig. 11. Optimal electrical network design for the large offshore wind farm presented in [2].

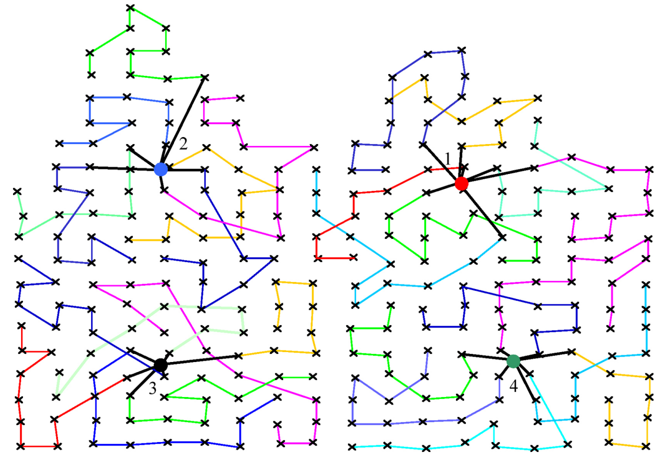

Fig. 12. Results of the optimal electrical network design for the large offshore wind farm using the approach proposed in this paper.

TABLE II
TOTAL COST OF THREE OPTIMAL SCHEMES

Scheme	Substations (MVA)	Cable Length (km)	Total Cost (USD)
Proposed approach	4 × 150 MVA	298.89	10.08×10^6
Improved GA [2]	4 × 150 MVA	324.07	$11.36 \times 10^{6(a)}$
Manual design [2]	4 × 150 MVA	339.12	$11.64 \times 10^{6(a)}$

[(a)] 1 RMB = 0.1491USD, values have been recalculated to include a profit of 3%.

B. Practical Case

In this section, the electrical network design: local WT collection and integration system, for an offshore wind farm of 280 2 MW wind turbines [2] is optimized using the model and method presented in this paper. Fig. 10 shows the results of the optimization presented in paper [2]. Four transformer substations and seven feeders in each one have been in order to compare results obtained with the proposed method and results published by others. Each substation services approximately 70 wind turbines distributed between seven feeders per substation.

The wind turbines in each feeder have been connected to the transformer substation considering the solution of the omTSP using GA, at the same time the interconnection system has been optimized, the result is shown in Fig. 11.

The main substation has a 150 MVA transformer with seven 35 kV bays and four 150 kV bays. The three offshore transformer substations are the same and possess seven 35 kV bays and one 150 kV bay. The optimal electrical network design for the wind farm is shown in [2], where the substation number 3 is marked as the main substation and 15 km is the distance from it to the point on the coastline where the undersea transmission system could be connected to the onshore power system.

In Table II, the economic index for the optimal solution obtained using the model and approach presented here is compared to an optimal solution presented in [2] (see Fig. 11) and the best manual design achieved.

The total cost shown in Table I corresponds to the annual cost, including equipment and construction but excluding power losses and operational costs. The results show the proposed approach is better in terms of total cable length and economy than the solutions presented in [2]. The discrepancy between results is produced by the use of different conductor types between sections in the feeder, it provides cost reduction. Furthermore, the star scheme for the integration system between offshore transformer substations provides the most economical solution.

V. CONCLUSION

A novel approach for solving the problem of optimal electric network design for large offshore wind farms is presented in this paper. It is based on improved GA with the inclusion of a modified version of the multiple traveling salesman problem. The main contribution of this paper is the use of the fixed-start and open-multiple traveling salesmen problem and a special chromosome-gene coding developed for this specific formulation, in order to solve the optimization problem of the electric network design for a large offshore wind farm. One special advantage of this approach is that it is fast and effective for radial configuration designs and provides the designer the opportunity to consider different cable cross sections in the design of the local WT collection system. This offers the opportunity to reduce the cost of the undersea cables used to support the offshore wind farm. Furthermore, an improved cost model has been presented which includes more realistic terms for the cost of the transformers connected to WTs, substation transformers and undersea cables. The optimization model and the solution algorithm have been tested with a hypothetical wind farm layout with different number of wind turbines and a large offshore wind farm that consists of 280 wind turbines of 2 MW. Results of the proposed approach demonstrate a satisfactory convergence for adequate level of fitness function, a relatively small number of generations for the case of large wind farms. Further improvement of this approach could be obtained including in the optimization problem the cost model including equipments, installation, operation and maintenance, for transformer substation, HV integration system, and transmission system.

TABLE III
COST PARAMETER FOR AC CABLES, FOR DIFFERENT VOLTAGES

Rated Voltage (kV)	α_3	α_4	β_2
35	72 845	1.0177×10^4	0.6585×10^6
150	377 145	3.2088×10^3	0.26481×10^6

APPENDIX

The cost parameters used in the cost models in this paper are shown in Table III.

The shipping and installation cost for the undersea cables is assumed to be 152×10^3 U.S.$/km [1]. The cost per unit for the step-up transformer at wind turbine is $C_{\mathrm{WT}} = 35.92 \times 10^3$ U.S.$, 690/35 kV, 2.2 MVA. The indicative cost estimate for one bay (which is defined here to include two feeders, at least) includes the following equipment: structures, busbar, circuit breaker (3) disconnectors, earth switches, surge arrestor, CT, VT, and so on. The cost of one substation bay at high voltage and medium voltage level is assumed to be $C_{HV,i} = 0.53 \times 10^6$ U.S.$ and $C_{MV,i} = 0.473 \times 10^6$ U.S.$, respectively.

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