Evaluation of optimal collection system and positions of offshore power substations of an offshore wind farm

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ABSTRACT. *In this paper, an approach based on genetic algorithm is presented in order to optimize the electrical layout of the collection system, as well as the positions of the offshore electrical substations of an offshore wind farm subject to some technical constraints. The objective is to minimize the investment part for the wind farm network which affects the price of the kilowatt-hour produced. The wind turbines are connected to the offshore electrical substations in radial network using medium voltage submarine cables with variable sizes. This radial network can have three different types of wind turbines clustering: chain, star or mixed string/star clustering. The presented work is useful during the plan phase of optimal electrical network configuration of an offshore wind farm.*

RÉSUMÉ. *Dans cet article, nous proposons une méthode basée sur un algorithme génétique pour optimiser la configuration du réseau interne ainsi que les positions des sous-stations électriques en mer d'un parc éolien offshore sous certaines contraintes techniques. L'objectif est de minimiser la part de l'investissement pour le réseau du parc éolien qui affecte le prix du kilowattheure produit. Les éoliennes sont raccordées aux sous-stations en réseau radial en utilisant des câbles sous-marins de moyenne tension à sections variables. Ce réseau radial peut avoir trois types de regroupements d'éoliennes différents : regroupement en chaîne, en étoile ou mixte chaîne/étoile. Le travail présenté est utile dans la phase amont de définition de l'architecture optimale du réseau électrique d'un parc éolien offshore.*

KEYWORDS: *genetic algorithm, Prim algorithm, optimization, offshore wind farm, electrical network, load flow.*

MOTS-CLÉS: *algorithme génétique, algorithme de Prim, optimisation, parc éolien offshore, réseau électrique, load flow.*

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1. Introduction

Offshore Wind Farm (OWF) is an attractive technology due to its many advantages compared to the onshore wind farm, such as: less visual, less effort to reduce the Wind Turbine (WT) noise, and larger energy production since the WTs at sea benefit from a stronger and more regular wind. Moreover, the offshore energy resource is particularly interesting in France, where the annual energy production is estimated at around 477TWh/year (Windtest, 1995). However, the price of the kilowatt-hour produced by this technology is affected by the total investment cost which is clearly larger compared with onshore wind park.

The electrical network efficiency and investment cost are influenced by its design, since different architectures may have different components that have different power losses and investment costs. The general configuration of the electrical network of an OWF is shown in the Figure 1.

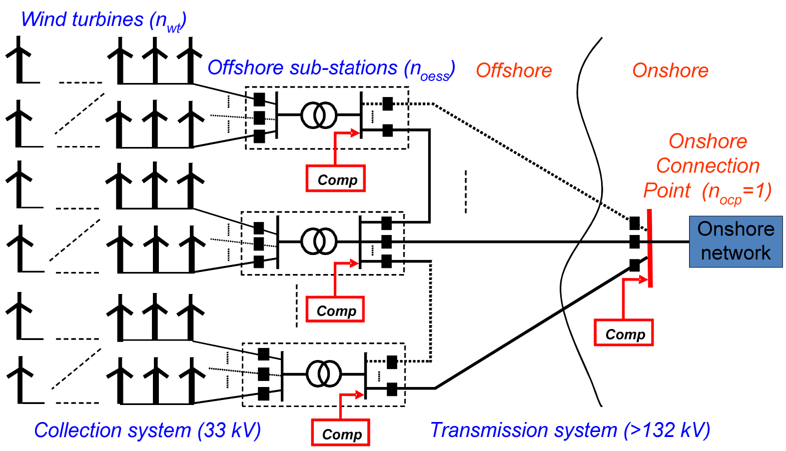

Figure 1. Electrical network of an offshore wind farm

The low-voltage output of each wind turbine generator, typically 690 V, is connected to a power converter used for regulation of the power and the voltage. Then, a first power transformer steps up the voltage level to a middle level. At that point, MV submarine cables (generally 33 kV) are used to connect all the groups of wind turbines to the MV bus-bars of the offshore electrical substations (OESS). This first part is called the collection system (Quinonez-Varela *et al.*, 2007). The power collected on each OESS is transmitted to the onshore connection point (OCP) with high voltage transmission system, either in HVAC (High Voltage Alternative Current) or in HVDC (High Voltage Direct Current).

Generally, the most common approach to determine the optimal electrical distribution system is based on the comparison of feasible schemes. The planners give initially several designs mainly according to their experiments and then technical restrictions are checked and costs are calculated for the selected schemes. However, this process is not “optimal” because the problem is non-linear, non-continuous and multi-variable (Li *et al.*, 2008). Consequently, the objective of this article is to develop a tool that can be used during the plan stage of the electrical network of OWFs. Several studies (Gonzalez-Longatt *et al.*, 2012; Lingling *et al.*, 2009; Zhao *et al.,* 2009) have been carried out in this field using various optimization techniques. Our approach is based on two optimization methods: the genetic algorithm (GA) and the Prim algorithm. A load flow calculation is used in order to check all the electric constraints of the network in steady state: transits of active and reactive power, voltage stability, and power loss.

This paper is organized in five sections. At first, we present the formulation of the optimization problem. In part 3, the two optimization algorithms used, genetic and Prim algorithms, are detailed. Section 4 focuses on the evaluation of network power loss. The performance of the optimization platform is studied in section 5, on real offshore wind farm build in UK, called: *Barrow Offshore wind farm (BOWF)*. This OWF is composed of 30 wind turbines of *3 MW* power each and one offshore electrical substation *33/132 kV*. Finally, section 6 concludes this paper.

2. Formulation of the optimization problem

The purpose of optimization is to find the optimal connection topology of the offshore wind farm network. Each network configuration is defined by the following four parts considered in the optimization:

– configuration of collection system,

– submarine cables sizes,

– positions of offshore electrical substations,

– compensation requirement in the transmission system side.

The choice of the adequate section of a cable that connects two nodes of the network depends on the power to forward through this connection. The submarine cables produces important amount of reactive power because of the significant value of the shunt capacitance. So, it is necessary to insert compensation equipment at the two HV link ends (*i.e.* at the OESS and OCP) in order to reduce the transit of reactive power. The amount of reactive power produced and the value of the necessary compensation depend on the configuration of the network and on the length of the HV connections. Consequently, this compensation is influenced by the positions of OESS. So, the optimization of the topology of the collection network is correlated with the HV transmission system by the positions of the SSEO, which complicates the problem. To simplify, the number of HV cables in parallel as well as the size of each HV cable are fixed. The only optimization variable on the HV side is the length of the link, which varies according to the positions of the EOSS.

2.1. Criteria and constraints of the optimization

Several criteria can be considered to design a power system. In this article, we focus on the minimization of two criteria, which are the investment cost and power loss on the network. This optimization is performed subject to some technical constraints to ensure a normal operation of the network. Firstly, the voltage at each network node must belong to the interval ± 5% of rated voltage. Also, the power transmitted in each link of the network must be smaller than the power limit of the cable used (this constraint is similarly applied to the power transformers of the OESS). Finally, we check a unity power factor at the onshore point connection.

Mathematically, the optimization problem is formulated as follows:

Minimize

$$F_{obj} = \frac{C_{inv}}{E_D} \qquad (€/kWh) \tag{1}$$

Where

$$C_{inv} = \frac{r(1+r)^T\, T}{(1+r)^T - 1}.Invest \qquad (€) \tag{2}$$

$$E_d = P_{prod}.(8760.T).\eta_p.\eta_T \qquad (kWh) \tag{3}$$

Subject to the following constraints

$$S_{i,j} \le S_{C\max}(c_s), \qquad i, j = 1,\ldots, N \tag{4}$$

$$S_{Tm} \in [S_{T\min}, S_{T\max}], \qquad m = 1,\ldots,n_{oess} \tag{5}$$

$$-5 \le \Delta V_{\max}(\%) \le +5 \tag{6}$$

$$0.98 \le PF_{OCP} \le 1 \tag{7}$$

$$P_{OESS} \in L_d \tag{8}$$

The objective function chosen F_{obj} is an aggregation of the two criteria: the investment cost $C_{inv}(€)$ and the average energy delivered to the onshore grid $E_d(kWh)$ which depends on the electric power loss of the network. This objective function represents the cost of the energy produced taking into account only the investment part for the electrical network, calculated by the ratio of the investment cost to the yearly average energy delivered. The total investment cost are calculated assuming that the total investment *Invest* is realized in the first year and paid during the lifetime T of the wind farm fixed at 20 years with an interest rate r of the bank of *4 %* (Lazaridis, 2005; Lundberg, 2006). The different investments parts considered on the total investment cost are: the cost of the MV and HV cables with variable sizes, the cost of the power transformers of the OESS, the cost of the compensation equipments, the cost of the MV and HV switch-gears of all the cables feeders, and an estimation cost of the offshore substations platforms (see the annexes 1, 2, and 3).

The total energy is calculated by the product of the theoretical maximum power P_{prod} delivered to the OCP (nominal production of all the wind turbines) per the total number of hours over the duration T ($8760.T$). The real production of the wind turbines rarely reaches the nominal power, since it depends on the wind resource of intermittent nature. So, we take into account the capacity factor η_p defined as the ratio of the real production in a year to the theoretical maximum production. Also, the unavailability of the electrical network due to the failures and maintenances is involved in the calculation of the average energy production by the availability factor η_T, which is the ratio of the number of operating hours to the theoretical maximum number of hours (8760 h).

The power $S_{i,j}$ transmitted from a node " *i*" to a node "*j*" among the N nodes of the network must be lower than the limit power $S_{Cmax}(c_s)$ which depends on the cable size c_s. Also, the apparent power of the power transformer S_{Tm} of each offshore substation "*m*" must belong to the pre-definite interval [S_{Tmin}, S_{Tmax}]. These two constraints are checked by the Equations (4) and (5). The power in each cable feeder $S_{i,j}$ depends on the number of the WTs connected to this link and the production of each one. In this paper, we consider that the number of WTs per group is one of the optimization variables. So, the condition (4) is used also to limit the number of WTs in all the clusters. The Equations (6) and (7) are used in order to check the constraint of maximum voltage difference ΔV_{max} in all the network nodes and to verify the constraint of power factor PF_{OCP} at the onshore connection point, respectively. Finally, the Equation (8) limits the research space of the offshore substations positions P_{OESS} in a pre-defined interval L_d.

2.2. Assumptions of the optimization

In order to simplify the optimization problem, the values of some network variables are fixed. The assumptions used are as follows:

– the number and the positions of wind turbines are fixed,

– the wind turbines are connected in radial form without redundancy,

– the number of offshore electrical substations is fixed,

– the number and sizes of HV cables are fixed,

– the voltage levels of MV and HV networks are fixed,

– the ratios η_p and η_T are fixed for all the network configurations,

– the network design is achieved for rated power of wind turbines.

2.3. Coding of a connection topology of the MV collection system

Each connection topology of the collection system is coded with a symmetrical adjacency matrix *AM* of size *NxN*, where $N=n_{wt}+n_{eoss}$ is the total number of nodes in the network, n_{wt} is the number of wind turbines and n_{eoss} is the number of EOSS. This matrix is divided into two sub-matrices as shown in Equation (9). The first sub-matrix AM_{WT} of size $n_{wt}xn_{wt}$, represents the connections between the wind turbines nodes and the second sub-matrix $AM_{EOSS\text{-}WT}$ of size $n_{eoss}xn_{wt}$, contains the connections between the wind turbines and the OESS nodes. An element $AM_{i,j}$, of this matrix is equal to "*1*" if the node "*I*" is connected to the node "*j*", otherwise this element is equal to "*0*". Each fixed matrix *AM* codes one connection topology of the collection system, and the set of the binary elements of this matrix *AM* constitutes an individual (or chromosome) *X* of the genetic algorithm. The method described in (Dahmani *et al.*, 2013a; 2013b) and illustrated in Figure 2, explains the transition from a connection topology of the internal network coded with an adjacency matrix *AM* to an individual *X* of the GA.

$$AM = \begin{bmatrix} \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ & \cdot & \cdot & & AM_{EOSS\text{-}WT} & \cdot & \cdot & \cdot & \cdot & \\ & & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ & & & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ & & & & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ & & & & & \cdot & \cdot & \cdot & \cdot & \cdot \\ & & & & & & \cdot & \cdot & \cdot & \cdot \\ & & // & & AM_{WT} & & & \cdot & \cdot & \cdot \\ & & & & & & & & \cdot & \cdot \\ & & & & & & & & & \cdot \end{bmatrix} \qquad (9)$$

Each node of the network can be connected only to its direct neighboring nodes (8 neighbors maximum for each node) according to its localization in the network. As example, using the described simplification for the set of nodes shown in Figure 2a, the node "5" can be connected to the set of nodes *{1, 2, 3, 4, 6, 7, 8, 9}*. But, the set of nodes *{10, 11}* cannot be linked to the node "*5*", since these nodes are not its direct neighbors. Using this condition for the remaining nodes of this example, we find that the total number "n" of elements in the symmetrical matrix AM (the some of the binary variables $AM_{i,j}$) is reduced to *24* instead of *55* elements without this condition calculated by the equation : $(N^2-N)/2$, where $N=11$ is the total number of nodes in the network.

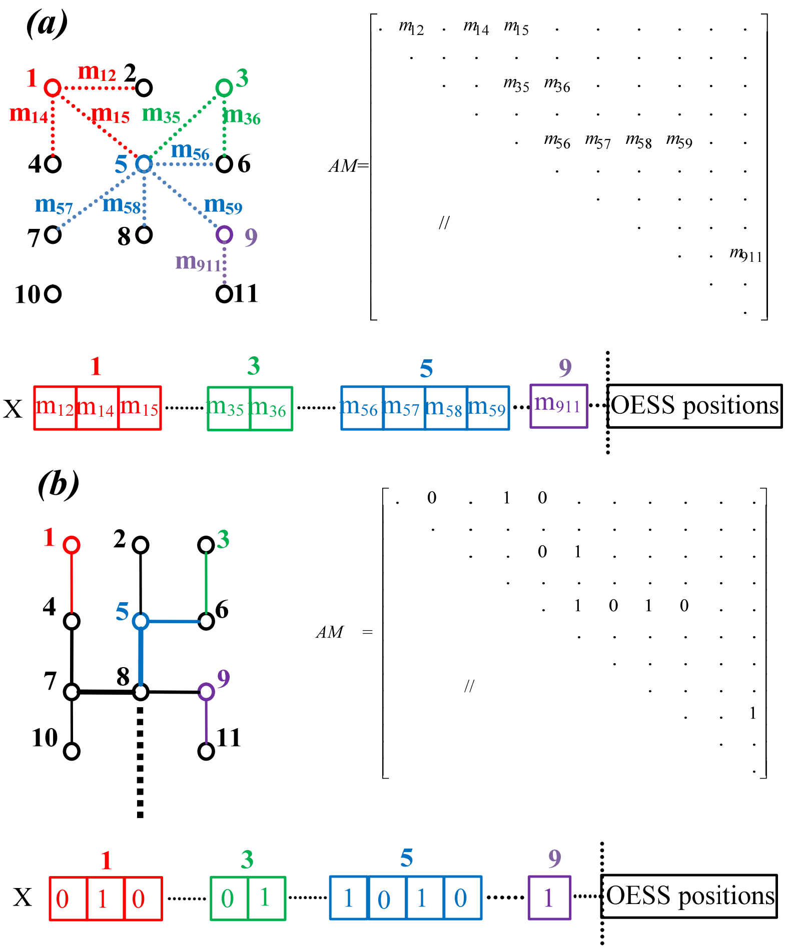

Figure 2. Transition method from a connection topology coded with a matrix AM to an individual X of the genetic algorithm: (a) method, (b) illustrative example

According to this simplification we reduce considerably the number of binary variables to fill in the matrix AM and thereby we reduce the number of possible configurations. This reduction of the search space is important because the theoretical number of possible topologies, in the case of fixed positions of the electrical substations, is equal to 2^n, where n is proportional to the total number of nodes in the network N.

The positions of all the offshore electrical substations $\{x_m, y_m\}$ in the network are also encoded in binary string of "$n_p=2.n_{eoss}.q$" bits, where q is the number of bits used for encoding each position x_m or y_m. Let $A_m = \{a_1, a_2, \ldots, a_q\}$ be a part of the vector X containing the "q" bits used to encode a position x_m (real variable) on the horizontal axis (or y_m on the vertical axis) of the electric sub-station "m". The decoding of this real x_m is realized as follows (Vallée and Yıldızoğlu, 2003):

$$x_m = x_{\min} + \frac{L_d}{2^q - 1} \sum_{k=1}^{q} a_k 2^{q-k} \tag{10}$$

Where x_{min} and x_m are the lower and upper limits of the real variable x_m, respectively, and L_d is the length of the interval between x_{min} and x_{max}.

3. Algorithms of optimization

As we explained previously, each topology of the internal network can be represented by a single matrix AM. Despite the reduction of the space of research, the number of realizable connection schemes from technical and economical point of view remains important, and it is difficult to generate all these network configurations in order to evaluate their performances one by one. Therefore, the use of optimization algorithms is required to generate and evaluate randomly the different connection topologies in order to find the optimal configuration without being forced to generate all the feasible architectures. In this part, we explain how to generate the two sub-matrices of the adjacency matrix AM using the genetic and Prim algorithms.

3.1. Genetic algorithm

The optimization problem described in the first section contains a large space of solution and a multitude of variables and constraints. So, meta-heuristic methods are adapted to solve such problems. The algorithm used in this article is the genetic algorithm. The idea is to generate the elements of the sub-matrix AM_{WT} and the positions of the OESSs starting from the GA. The n binary variables of the network topology (sub-matrix AM_{WT}) and the n_p bits of the OESSs positions are encoded into the same vector X as shown in Figure 3. Each vector X constitutes an individual or chromosome of the GA and represents one network configuration. So, the objective of the optimization is to compare the different individuals in order to find the best chromosome X that represents the best connection topology of the collection system.

The three main operators of the GA are selection, crossover and mutation. Each operator is used in the optimization with a certain probability. The values of these probabilities are very important for the success of the optimization, because they influence the evolution of the initial population, by selecting the best individuals for the reproduction, and ensure the individuals diversity to avoid premature convergence towards a local minimum. The selection technique chosen is hybrid between the "elitist" and the "roulette wheel" (Moreau, 2005). The best individual of each generation is ensured to survive the next generation.

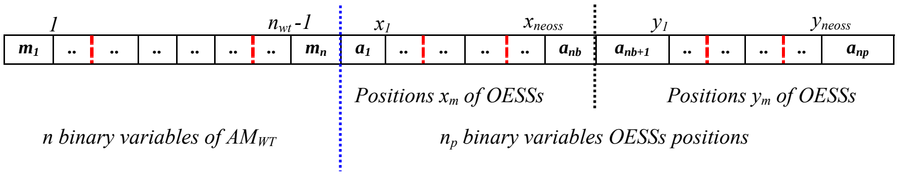

Figure 3. Representation of an individual of the GA

The operators of crossover and mutation allow creating new individuals. The method of crossover used is called multi-point crossover. This technique provides several sites of crossing and it is well adapted to our application where the length of an individual is important.

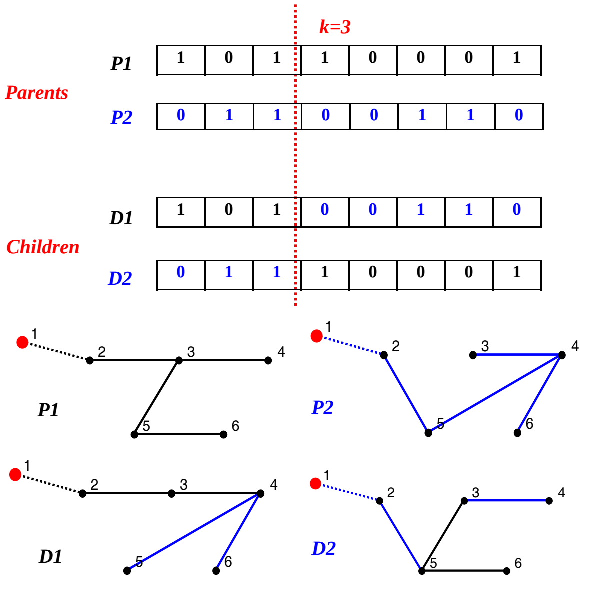

Figure 4. Individuals reproduction using crossover operator (one crossing site K=3)

An example of crossing on only one site is shown in Figure 4. The crossing between the two connection topologies of the parents *P1* and *P2,* generates two new topologies (children *D1* and *D2*) by exchanging a part of the binary strings between the parents (branches in our case).

The mutation acts in a random way on one or several bit(s) of an individual, by changing its value from "*0*" to "*1*" or conversely, according to a very weak probability ranging between *0.001* and *0.01*.

3.2. Algorithm of Prim

To accelerate the convergence of the GA, Prim's algorithm used in graph theory is introduced as a local optimization in the collection system. This algorithm allows finding a minimum spanning tree in a weighted connected and undirected graph $G=(V, E)$, where V is the set of vertices and E the set of edges of the graph (Prim, 1957). The distribution of wind turbines on a branch (cluster) meets this definition. Therefore this algorithm can be applied to connect each wind turbines group to the nearest electrical substations in Minimum Spanning Tree (MST).

The different graphs G_i arise from the individuals generated by the GA. Each individual X can generate a number n_g of graphs G_i equal to the number of wind turbines clusters in the OWF network, ranging between "*1*" and "n_{wt}". Each graph G_i gathers a number of wind turbines nodes to be connected to the OESS node by the Prim algorithm in MST graph. In case of several OESSs, the global graph of the collection system of the offshore wind farm is not a connected graph, but all the wind turbine nodes connected to one EOSS node constitute a connected graph that can be divided in several clusters (graphs G_i) used to evaluate their MSTs using the Prim algorithm.

The procedure of building the MST graph between each set of wind turbines nodes (cluster) and substation node is described by the following algorithm:

Algorithm 1. Algorithm used to build the MST graph

```
V←V
E←E
V'←∅
E'←∅
n← r_m                    (choose OESS node),
V'← add (n, V)
V← delete (n, V)
Do while (V ≠∅)
    x ← E_{n, m}          (find the shortest connection E_{n,m}, where n ϵ V' and m ϵ V)
    V'← add (m, V)
    E'← add (x, E)
    V← delete (m, V)
end while
MST ← G (V', E')
```

The GA provides the first connection topology only among the wind turbines (sub-matrix AM_{WT}) and provides also the OESS positions. From this sub-matrix, the different clusters of the wind turbines are identified. Then, the Prim algorithm is used to build each MST between each WTs cluster and the nearest OESS. This step enables to fill the second sub-matrix $AM_{OESS\text{-}WT}$ and to modify the first sub-matrix AM_{WT}. The possible configurations of each MST are: string connection, star connection, or mixed string/star connection, as shown in Figure 5.

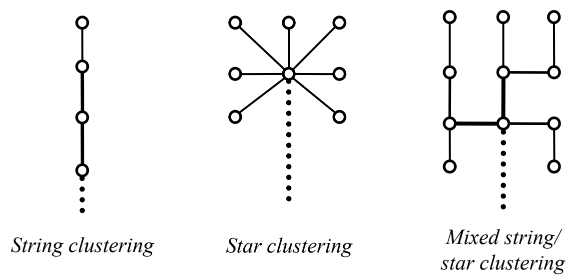

Figure 5. The different configurations of wind turbines clustering

The MSTs have radial configurations, so, the power transmitted in each cable link can be estimated. This estimated power is used to choose the appropriate sections of the MV cables and thereby to generate the electrical parameters (resistance, inductance and capacitance) of each cable segment required for load flow calculation.

Using this approach, the number of clusters of wind turbines connected to each OESS and the number of wind turbine in each cluster are considered as two variables to be optimized in terms of investment cost and power loss.

4. Evaluation of the power loss in the electrical network

The amount of power loss is a very representative variable in the plan phase of the power system (Zubiaga *et al.*, 2009). To evaluate the power losses of the wind farm network (collection and transmission system), the load flow is calculated for each configuration of the network using the Newton-Raphson (NR) method for the resolution of the system of following equations (Zhao *et al.*, 2009):

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = -[J] \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \tag{11}$$

The algorithm takes as inputs: the matrix of connections *AM*, the injections of active and reactive power at all the network nodes, and the electrical parameters of the MV and HV cables, the transformers, and the compensations. The outputs are the modules and the phases (*V* and *α)* of voltages at all the network buses. The network power losses are evaluated knowing these two outputs (*V* and *α)* and the different components data. Each component of the network (MV cables, HV cables, transformer, and compensation equipment) is represented by a Π model. In submarine cables, three types of power losses are taken into account: Joule loss in the copper, the screen loss and the armor loss.

The WT generator is modeled as a node *PQ*, represented by a production of active power *P* and a reactive power *Q*. Different generator (DFIG, SCIG, PMSG...) may have different PQ characteristics that depend on the wind speed and in fact can play a role in the optimization. The raison is that a part of the reactive power of the collection system can be controlled by the WTs generators, which can improve the sizing of the reactive power compensation equipment installed at the OESS. However, including the PQ characteristic of the WT generator in the optimization increases significantly the simulation time since each network configuration will be evaluated for several wind speed states. Therefore, the optimization is achieved for only one operating point PQ for all the WTs.

The compensation amount estimated for each network configuration is inserted at the transmission system before the load flow calculation in order to reduce the power loss due to the transit of the reactive power in the links.

5. Example of study

In order to validate the performance of the presented approach, a study was achieved on an offshore wind park built in UK, called *Barrow offshore wind farm* (BOWF). The technical details on the electrical network of this park are given in (Lorc knowledge website). The objective of this study is to find another connection topology of better performances than the actual layout presented in Figure 6. The parameters values of the simulation are summarized in Table 1.

The optimal connection topology of the network obtained by the optimization is shown in Figure 7. As can be seen, the actual and proposed layouts are different in both the connection topology of the collection system as well as in the position of the offshore electrical substation. The central position of the OESS optimizes both the lengths of the MV and HV cables. The optimal sizes of the MV cables found are: *25* segments of *3x12 0mm²* and *5* cable segments of sizes: *3x185 mm²*, *3x240 mm², 3x300 mm², 3x400 mm²* and *3x800 mm²*.

The technical and economical comparisons of two network layouts for BOWF are presented in Tables 2 and 3, respectively. As can be noted, the two configurations satisfy the pre-defined constraints: a unity power factor at the OCP and a maximum voltage difference belonging to the interval ± 5% of the nominal voltage fixed by the grid code. However, the optimal cables sections used in the proposed layout allow decreasing the power losses by 7.15%, which increase the energy production.

Table 1. Simulation parameters

Quantity	Symbol	Value
Number of wind turbines	n_{wt}	30
Active power of WT [MW]	P	3
Reactive power of WT [MVAr]	Q	0
Number of offshore substations	n_{oess}	1
Voltage levels [kV]	MV/HV	33/132
Number of HV cables / sections	$n_{HV}/c_{s\text{-}HV}$	1/3 x 400 mm²
Number of bits to encode the connections	n	86
Number of bits to encode the OESS positions	n_p	22
Interval of OESS positions [km]	L_d	[0, 20] / 2
The network availability [%]	η_T	95
Capacity factor of the OWF [%]	η_P	40

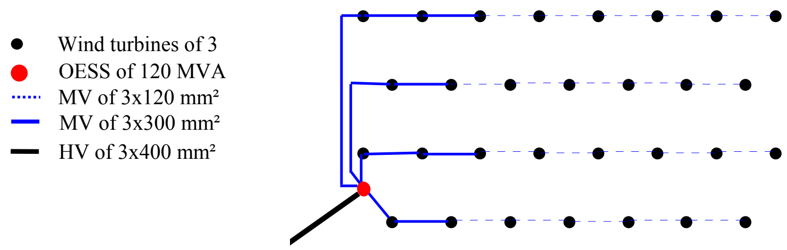

Figure 6. Actual layout for BOWF network

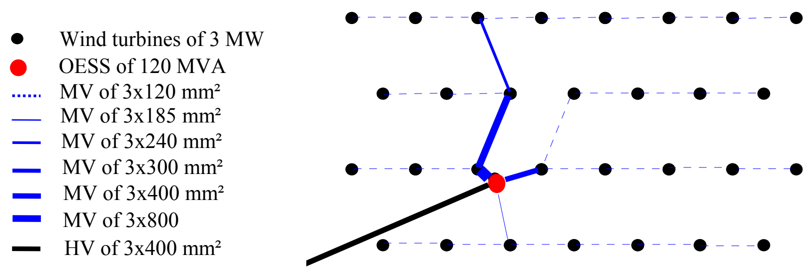

Figure 7. Proposed layout for BOWF network (Optimization result)

Table 2. Technical comparison of the two layouts for BOWF network

Quantity	Actual layout	Proposed layout
Total length of MV cable [km]	16.85	15.58
Total length of HV cable [km]	7.56	8.58
Number of wind turbine clustering (n_g)	4	3
Number of wind turbine per group	{8, 7, 8 ,7}	{14, 9, 7}
Power losses [MW]/efficiency [%]	1.007 / 98,88	0.935 / 98,96
Power factor at the OCP (PF_{OCP})	1.00	1.00
Maximum voltage difference (ΔV_{max}) [%]	1.11	1.02
Production [GWh/year]	294.57	294.82
Compensation at the OESS [MVAr]	5.91	5.44
Compensation at the OCP [MVAr]	4.14	4.66

Table 3. Economic comparison of two layouts for BOWF network

Quantity	Actual layout	Proposed layout
Objective function [c€/kWh]	0.5542	0.5375
Total investment cost [M€]	32.65	31.69
Production price over 20 years [M€]	1222.09	1223.0881
Net profit over 20 years [M€]	1189.44	1191.3931
Investment gain [M€]	Reference	0.9539
Total gain over 20 years [M€]	Reference	1.9536

Moreover, in the optimized layout, a gain of *954 k€ (2.94%)* is saved on the investment cost and a gain of *1 M€ (0.08%)* is realized on the production price compared to the actual layout. Finally by comparing the net profit of the two network configurations, a profit of *1.95 M€* is carried out over the total lifetime of the wind farm.

6. Conclusion

The trend is to build large-scale offshore wind farms or interconnected multi-parks with several offshore electrical substations in order to facilitate the management of energy production. However, on the one hand, the investment cost is larger compared to onshore wind farm, which has a direct impact on the production cost. On the other hand, the technical constraints are more dominating at sea. The submarine cables used in the MV collection system and HV transmission system are usually three-core cables in order to reduce the installation cost. But this cables configuration brings some technical constraints such as: reactive power production, voltage regulation, power losses, maintenance… For these reasons, the optimal network design of the OWFs using intelligent methods attracts the attention of the industry and research, particularly the design of the electrical connection.

The approach presented in this article is useful during the design phase of the offshore wind farm network. Its performance was evaluated by the study carried out on a real offshore wind farm. First, this model allows optimizing the connection topology of collection system. Three radial configurations are considered for wind turbines clustering: string, star, and mixed string/star clustering. Also, the optimal positioning of offshore electrical substations is involved in the described approach.

Using this approach, the optimal configuration of the AC network that minimizes both the investment cost and the power loss can be assessed, subject to some technical constraints in order to ensure normal functioning of the optimal electrical network.

Actually our study is focused on the reliability issues in order to improve the availability in the case of failures or maintenances by incorporating the redundancy in the electrical network (Dahmani *et al.*, 2014).

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Annexes

Annex 1. Cost of the submarines cables

The cable cost C_{cable} is proportional to the length L_c and to its power limit $S_{cmax}(c_s)$ which depends on the cable size c_s and the voltage level. It is given as follows (Lundberg, 2003):

$$\begin{aligned} C_{cable} &= \left(C_{SI} + C_C(c_s)\right).L_c && (€) \\ C_C(c_s) &= \mu\left(\alpha_c + \beta_c\, e^{\gamma_c 10^{-8} S_{c\max}(c_s)}\right) && (€) \end{aligned} \qquad (12)$$

Where C_{SI} is the shipping and installation cost fixed at *117 €/m* (Nandigam and Dhali, 2008), $C_C(c_s)$ is the cable cost according to the section c_s. The cost parameters α_c, β_c and γ_c depend on the voltage level as shown in table 4, and $\mu=0.1155$ is a conversion factor from the SEK (Swedish krona) to the €.

Table 4. Cost parameters [SEK] of the 33 kV and 132 kV cables (Lundberg, 2003)

	α_c	β_c	γ_c
33 kV	$0.411\ 10^6$	$0.596\ 10^6$	$4.1\ 10^6$
132 kV	$1.971\ 10^6$	$0.209\ 10^6$	$1.66\ 10^6$

Annex 2. Cost of offshore electrical substation

The cost of the offshore electrical sub-station C_{OESS} is composed of: transformer cost (C_T), costs of MV and HV switch-gears (C_{SGMV} and C_{SGHV}), and an estimate cost of the OESS platform (C_R). It is given as follows:

$$\begin{aligned} &C_{EOSS} = C_T + C_{SGMV} + C_{SGHV} + C_R && (M€) \\ &C_{SGMV} = C_{SGMVb}\, N_{MVb} \quad , \quad C_{SGHV} = C_{SGHVb}\, N_{HVb} \end{aligned} \qquad (13)$$

Where CSGMVb and CSGHVb are the costs of MV and HV switch-gear bays, NMVb and NHVb are the number of MV and HV bays. The costs of the MV and HV bays are respectively: CSGMVb=0,364 M€ and CSGHVb=0,408 M€ (Gonzalez-Longatt *et al.,* 2012).

The transformer cost (C_T) and the estimation cost of the platform (C_R), depend on the nominal power of the power transformer (S_{Tn}), these costs are given by the following equations (Lazaridis, 2005; Zubiaga *et al.*, 2009):

$$C_T = 0.03327\ S_{Tn}^{\ 0.7513} \qquad (M€)$$
$$C_R = 2.14 + 0.0747.S_{Tn} \qquad (M€) \tag{14}$$

Annex 3. Compensation cost

The compensation equipment considered in this paper is the static compensation, placed at the two ends of HV transmission system. The addition of a static compensation in the network of the OWF increases the investment cost, on the one hand, by the compensation equipment cost itself (C_{EC}), and on the other hand by an increment ($C_{incremt}$) of the platform cost. These two terms are respectively proportional to the quantity of total reactive power compensation Q_{Comp} *[VA]* on one hand, and proportional to the rated value of the static compensation installed at each substation $Q_{comp,eoss}$ *[kVA]* on other hand. The total costs of compensation C_{comp} is given as follows (Guidi and Fosso, 2012):

$$C_{comp} = C_{EC} + C_{incremt} \qquad (M€)$$
$$C_{EC} = -0.136\,10^{6} + 241.5\,Q_{comp}^{\ 0.447} \tag{15}$$
$$C_{incremt} = 608\,Q_{comp,eoss}^{\ 0.765}$$