Optimization of Electrical Connection Scheme for Large Offshore Wind Farm with Genetic Algorithm

Huang Lingling, Fu Yang and Guo Xiaoming

Abstract--**Offshore wind farms have great potential as large-scale sustainable energy sources for the production of electricity. Utilization of offshore wind farms requires a reliable and efficient transmission system. The increased interest in offshore wind farms accentuates the need to focus attention on the economic issues of the electrical system. Based on analysis of existing offshore wind farm schemes and the investment cost of electrical components, optimization model is proposed and explained in this paper. An optimization approach based on genetic algorithm is presented to search for the optimum connection scheme. A calculation example shows that the differences among different electric connection schemes are evident, and by use of genetic algorithm the optimal connection scheme can be found effectively.**

***Index Terms*—Optimization, offshore wind farm, electric connection scheme, genetic algorithm**

I. INTRODUCTION

Offshore wind power exploitation becomes the highlight of recent renewable energy development for the following reasons: 1) Offshore windmill will not take up valuable land recourse and free of noise pollution; 2) Wind flow will not impede by land structures thereby strongest wind power and longest utilization can be delivered; 3) Offshore wind turbine has bigger single unit rated power than onshore one. So far, there are 19 offshore wind farms in the world and there is a tendency to build larger wind farms. The recent built offshore wind farms, Nysted and Horns Rev have installed capacity of 165.6MW and 160MW respectively [1].

However, the total investment of an offshore wind farm is typically 30%~60% higher than an onshore wind farm of the same capacity. First, the location of offshore wind farms is always 10km away from land, where has a water depth of 10m. Hence the submarine cable is indispensable in the wind energy transmission system. Second, One or more in-site sea substation is needed to harness and transmit the wind energy if the scale of the wind farm is large enough. Finally, the construction and maintenance of an offshore wind farm need some specialized equipments, which are always expensive. Therefore, optimization of electrical connection for offshore wind farms will remarkably reduce the total cost. Reference [2] investigated layouts of various large-scale wind parks (using both AC and DC). In [3-4], the main compositions of wind farm investment are analyzed, and then a genetic algorithm approach is used to solve a HVDC layout of a DC offshore wind farm. However the configuration of each cluster and the physical layout of sea substation are neglected. Also an improved genetic algorithm is introduced in [5] for optimizing the electric system of large offshore wind farm, but there are no detailed descriptions of electric components.

In this paper, a typical offshore wind farm, Horn Rev, has been studied in depth. And the investment cost of electrical components for offshore wind farm have be categorized and concluded to be a group of simple arithmetic expressions concerning the number and locations of wind turbines and the prices of each component. Hence, the optimization of electric connection scheme is transformed into be a problem of optimizing a group of factors, which are ① the voltage level inside the wind farm, ② the voltage levels of substation, ③ the number of substations, ④ the locations of substations, ⑤ the connection topology of substations, and ⑥the connections topologies of turbines. Most of these factors are discrete, highly nonlinear and coupling with each other, which means the optimization of electrical connection scheme for large offshore wind farm can hardly be achieved by solving arithmetic equations. While in the other hand, genetic algorithm with the attributes of random accessing and global optimization, is capable of solving discrete multi-variable equations. An optimization example of an offshore wind farm with 580 wind turbines show that the optimization approach based on genetic algorithm is suitable and valid.

II. OPTIMIZATION MODEL

The electric system within an offshore wind farm and its connection to the main power system pose new challenges to the experts. As the wind farm tends to be bigger, the economic problem attracts more attention. The objective of this work is to find the optimum system planning for the given offshore wind farm with a minimum cost. The Horns Rev as the first large offshore wind farm in the world, the electric system within the wind farm and its connection to the main power system is shown in Fig.1 as a typical example [6].

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The optimization can be described as:

Minimize E_{cost}

Subject to $S_{branch} \le S_{\max}$

Where E_{cost} is the cost of the electric system in the wind farm, S_{branch} is the apparent power flowed in every transmission and sub-transmission line, and S_{max} is the maximum apparent power every line can transmit.

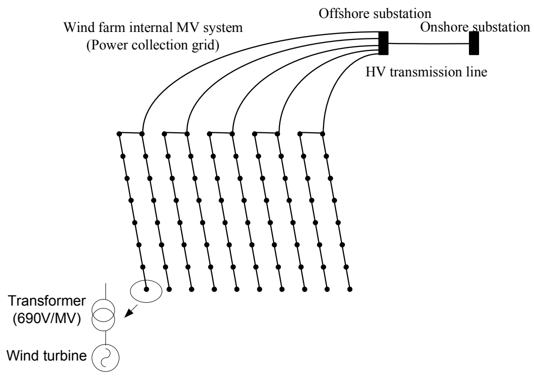

Fig.1. Offshore wind farm layout of Horn Rev in Denmark

In order to concentrate on the key issue, the economics of electric system, it takes a few assumptions here:

(1) The power system stability and the power flow distribution are not considered here.
(2) 'N-1' deterministic criterion is not used for transmission system planning.
(3) There is no space limitation for the laying of marine cables.

Hence, the cost of electric system within an offshore wind farm can be categorized into three main parts.

A. The cost of transformers connected to wind turbines C_1

$$C_1 = p_1 N \qquad (1)$$

Where, p_1 is price of the transformer, and N is the number of wind turbines in the wind farm. Currently, most wind turbine generators operate at a generator voltage level of 690V. Transformers installed directly in or close to the basement of each wind turbine step up the generator voltage level to a medium voltage level, usually 10kV or 35kV in China [7].

B. The cost of substations C_2

C_2 covers all cost of the offshore substations. Take the substation i for example, the cost C_{2i} can be described as

$$C_{2i} = b_{hi} n_{hi} + b_{li} n_{li} + p_{2i} m_i + E_i + S_i \qquad (2)$$

Here, b_{hi} and b_{li} are the prices of bays of high voltage and medium voltage level respectively which are determined by the voltage levels of the substation. n_{hi} and n_{li} are the numbers of the bays. P_{2i} is the price of transformer that is determined by its capacity and voltage level. m_{i} is the number of the transformers in the substation which is influenced by the collecting capacities of wind turbines and the rated capacity of transformers. According to practical engineering experiences, m_{i} is set to be 2 here. E_i is the cost of corollary equipments such as protection relays, the station control equipment and so on [8]. S_i is the construction cost for the substation which can be calculated as

$$S_i = p_3 (m_i k_1 + n_{hi} k_2 + n_{li} k_3) \qquad (3)$$

Where, k_1 is the equivalent construction area of a transformer, k_2 is the equivalent construction area of a high voltage bay, k_3 is that of the medium voltage bay and p_3 is the unit price of construction.

C. The cost of marine cables C_3

In a large offshore wind farm, there are two types of marine cable: the medium voltage cables in the power collection grid collecting electricity generated by the wind turbines and the high voltage transmission lines connecting the substations and transmitting power into the network. So the cost contains two aspects as well,

$$C_3 = C_{31} + C_{32} \qquad (4)$$

Here, C_{31} and C_{32} are the costs of medium voltage cables and high voltage cables respectively.

In onshore wind farms, the electrical system configuration is usually decided by the turbine and substation positions, and the site track routes. Offshore, there is more freedom. Figure 2 illustrates the most widespread arrangement of wind turbines in the internal MV system. The number of wind turbines in this radial array connected to the PCC point lies on the maximum power that can be transmitted by the marine cable [9].

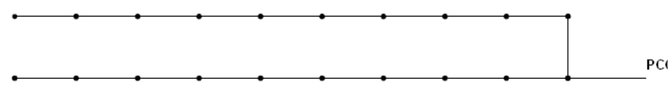

Fig.2. Radial cable arrangement

Considering that the closer to the PCC point, the more power the cable transmitted, cables with different sections in a radial array certainly will save the expenses. So the cost of MV cables can be obtained as

$$C_{31} = \sum_{j=1}^{n} p_4(j) l_j \qquad (5)$$

Where, n is the number of segments connecting two wind turbines, l_j is the length of the cable j, and $p_4(j)$ is price of the cable j determined by the cable section.

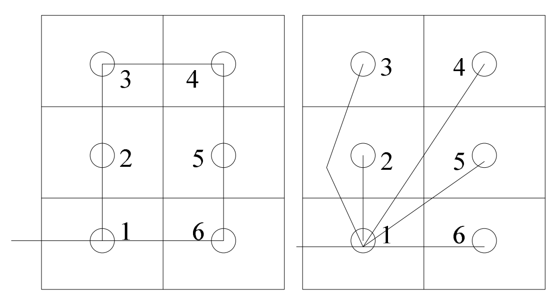

Fig.3 Interconnection of offshore substation

Wind farms tend to be bigger and the distance to the shore or to the next (offshore) transformer station is significantly longer than for onshore wind farms. Therefore, high voltage levers will certainly be useful for offshore applications in order to minimize power losses. But higher voltage levels mean bigger cable section and more expenses. So the C_{32} is considered in this paper and it can be calculated in the same way as C_{31}.

In offshore wind farms, there are two ways of the connections between substations, illustrated in Fig.3. Here, the substation collecting the electricity generated by the entire wind parks to the onshore network is called central substation, such as substation 1 in Fig.3. The substation collecting part of the electricity and transmitting to the central substation is called terminal substation, such as 2~6 in Fig.3. There is only one difference between central and terminal substation which is the number of bays in the high voltage level.

The above description of electric system in the large offshore wind farm shows that the whole cost is influenced by: ①the medium voltage level; ②the high voltage level;③the number of substations;④the positions of substations;⑤the connection manner of the substations;⑥the number of wind turbines in a radial array and ⑦the topological connections between wind turbines. Hence, the optimization problem can be greatly facilitated by the classification of cost calculation into two categories: a group of discrete variables optimization and optimal routes selections. As routes optimization had been fully discussed in graph theory [10], and for gaining concentration on the key problem, genetic algorithm is introduced to solve the discrete variable optimization. Fig. 4 shows the flowchart.

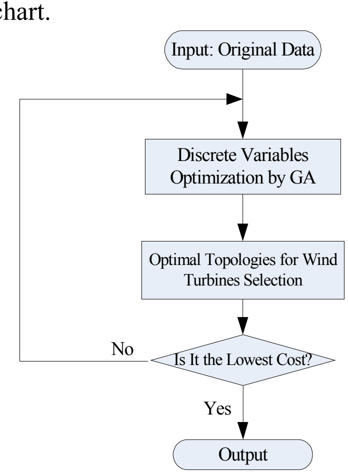

Fig.4 Flowchart of the optimization system

III. GENETIC OPTIMIZATION

Genetic Algorithm (GA) is a novel optimal algorithm based on Darwin's evolution thought. It emulates the rules of biological evolutionary process, such as reproduction, gene mutation, and natural selection, etc [11]. As a mathematic model of evolution, GA is of its special efficacy on the searching and optimizing problems which have huge solution spaces. The GA approach to optimize an offshore wind farm is drawn under the following general lines:

A. *Variables and Chromosome Coding*

GA is composed of populations of strings, or chromosomes and three evolutionary operators: selection, crossover, and mutation. The chromosomes may be binary coded. Each chromosome is an encoding of a solution to the problem at hand representing an electric connection scheme here. As shown in Fig.5,

X_1: = 1: the medium voltage level is 10kV.
= 0: the medium voltage level is 35kV.

X_2: = 1: the high voltage level is 110kV.
= 0: the high voltage level is 220kV.

X_3: = 1: there is at least one offshore substation in the wind farm.
=0: there is no offshore substation in the wind farm.

X_4: = the number of offshore substations (X_3=1).

X_5: = 1: star connection between offshore substations ($X_4 \geqslant 3$).
=0: ring connection between offshore substations ($X_4 \geqslant 3$).

X_6: = the number of wind turbines in a radial array (there is 1 wind turbine in variation which means the actual number of wind turbines connecting to an array is X_6 or X_6+1).

Note: X_6 will be affected by X_1 and X_2, whereas the maximum and minimum cable sections are determined. Take the coding of chromosome in Fig.5 for example, it represents a network with 7~8 wind turbines per array, 35kV gird collecting the power generated by wind turbines and transmitting to three 35kV/220kV step-up offshore substations which are in star connection.

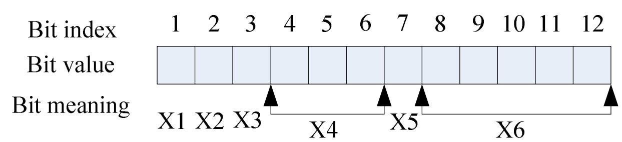

Fig.5 Coding of chromosomes

B. *Fitness*

In GA, the new generation of the population is computed using the fitness of the individuals in the current generation. The highly fit population is with a greater fitness. The fitness which is the reciprocal value of the whole cost of the offshore wind farm can be calculated as:

$$F = \frac{1}{E_{\cos t}} \tag{6}$$

Where, $E_{\cos t} = C_1 + C_2 + C_3$. Apparently, the less the cost is, the higher opportunity the population will be evolved.

C. *Selection*

In this work, the rank-based selection is employed [12]. The chromosomes including the original, mating and crossover population are ranked according to their fitness value. The individuals with higher value will be selected with more probability.

IV. CASE STUDY

In this section, an offshore wind farm installed 580 wind turbines has been setup, each turbine rated as 2MW. The distance to shore is about 15km between the nearest wind turbine and the coastline.

While planning this large offshore wind farm, the main task is to design the electric collection and transmission system. As the special shape of the coastline, the wind farm is not with the regular shape as the normal one. In order to obtain the optimal scheme, automatic optimization algorithm and the program must be developed and applied.

In Fig.6, it is shown that wind turbines are divided into 6 substation areas. The central substation installs a transformer of 240MVA, 8 bays of 35kV and 6 bays of 220kV. The terminal substations install the same capacity of 240MVA, 8 bays of 35kV and 1 bay of 220kV.

In each area, there are about 97 wind turbines. These wind turbines are divided into 8 radial arrays. Each array comprises 12~13 wind turbines and transmits electric power to the step-up substation using 35kV marine cable. Then the 220kV cables are used to connect the terminal substations to the central one in a radial way and to transmit power to the onshore network.

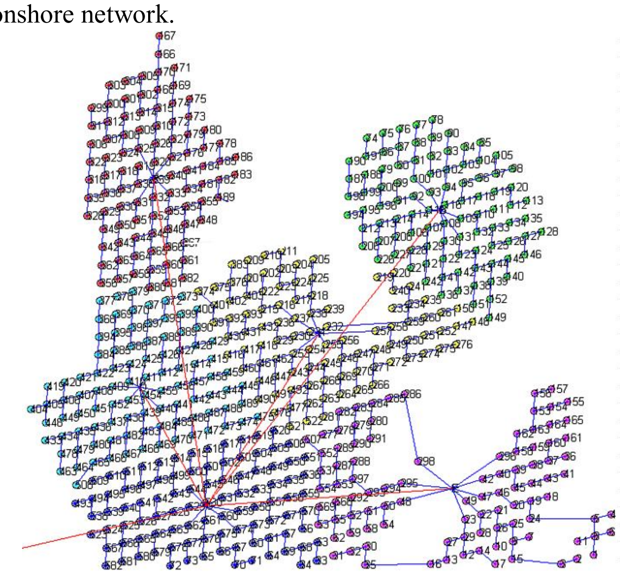

Fig.6 Optimal electric distribution network of the wind farm

V. Conclusion

As the characteristics of the electric system of an offshore wind farm are concerned, the design is composed of series of choices determined by the voltage levels of the collecting grid and the transmission system, the number, locations and connection scheme of offshore substations and the number of wind turbines per array and their topologies. The economic optimization is classified into two categories: a group of discrete variables optimization and optimal route selections. A case with 580 wind turbines clearly demonstrates the effectiveness of introducing GA into searching the optimal electric connection scheme.

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VII. Biographies

Huang Lingling was born in Zhejiang, China. In 2004 and 2006, she graduated from Xi’an Jiaotong University and received her master degree from Zhejiang University, both in electrical engineering, respectively. She is now working as a lecture in Shanghai University of Electric Power, Shanghai, China. Her area of interest includes protection relays and wind power generation system.

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Guo Xiaoming was born in Jiangxi province, China, on Oct 20, 1980. In 2001, 2005 and 2008, he received his B.S, M.Sc and PhD degree from Zhejiang University, all in electrical engineering. Now he is a research engineer in GE global research center, Shanghai. His special field interest included power system stability, relay protection and renewable energy generation.