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Analysis of the Switchgear Configuration for the Ring Collection Grids of Offshore Wind Farms

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Abstract. In order to explore the factors that affect the reliability and cost of the collection grids, we consider the ring topology of collection grids for offshore wind farm. Reliability evaluation model and cost model considering the connection among the cables, switchgears and wind turbines were established according to switch configuration scheme. The reliability and cost were contrasted of the partial switchgear configuration and the complete switchgear configuration of ring topology. On this basis, when the number of switchgear is unknown the reliability evaluation model and cost model of the partial switchgear configuration are established. Considering the reliability and cost, the NSGA-II algorithm is used to achieve the Pareto optimality, and the optimal partial switchgear configuration scheme is designed.

1. Introduction

As a clean energy, wind power has become one of the fastest developing energy nowadays [1]. Because of the abundant wind resources and high wind speed, the offshore wind farms have become the main trend of wind energy. In offshore wind farms, wind turbines are connected by cables to form a collection system, and the collected power is transferred to substations, and then merged into the power grid through booster stations. The collection system is a key part of connecting the wind turbines with the power grids which affects the efficiency and reliability of the offshore wind farm,. Because of its high cost, the ring topology affects its practical application, and the existing research results are few.

At present, some domestic and foreign scholars have studied the topology for collection system of offshore wind farm. In [2], the most widely used radial topology is analysed, and the corresponding reliability evaluation model is proposed according to the number of switchgears. In [3], the economic optimization models of radial and ring structures are established, and the optimal structures are selected for reliability evaluation, which provides an effective method for network planning of collection system. In [4], the reliability model for collection system of wind farms based on reserve and equivalent wind turbine model is proposed, but the reliability is not analysed according to topological structure. In view of the above research, this paper considers the use of NSGA-II algorithm to achieve the Pareto optimization between the two models, and designs the optimal switchgear configuration scheme based on the establishment of reliability and cost model of partial switchgear configuration.

2. Collection grids of offshore wind farms

There are three kinds of wiring modes for collection system of offshore wind farms, including radial, ring and star [5]. Because of its high reliability, ring structure will have more application value in offshore wind farms. Because of its high cost, ring structure has few applications in wind farms. Fig 1. is a simplified topological map for collection system of London Array. The London Array is a 175 turbine 630 MW offshore wind farm located 20 km off the Kent coast in the outer Thames Estuary in the United Kingdom.

In the offshore wind farm equipment, wind turbines, cables and switchgears play important roles in the collection system. Because of its particularity, ring topology can only be divided into two kinds of switchgear configurations including partial switchgear configurations in fig 2(a), and complete switchgear configurations shown in fig 2(b). As shown in Fig 2., compared with some switchgear configurations, the complete switchgear configuration costs a lot, but at the same time the reliability is improved.

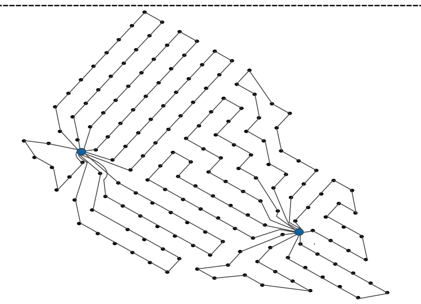
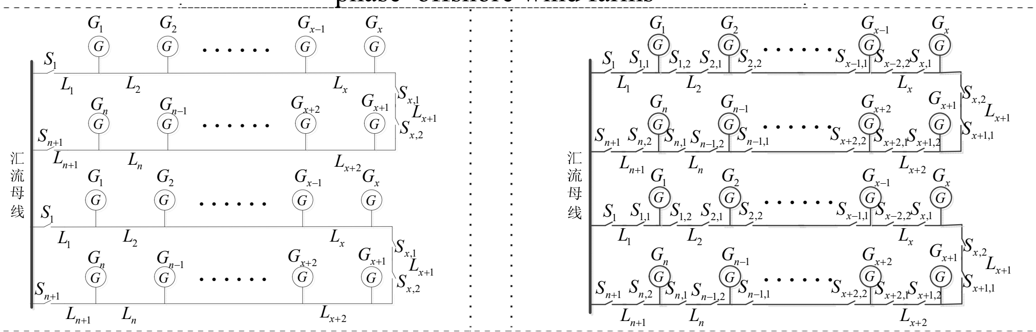


Figure 1. The collection system of London Array phase offshore wind farms



(a). Partial switchgear configuration of ring topology

(b).Complete switchgear configuration of ring topology.

Fig 2. Switchgear configurations based on ring layout

3. Reliability assessment for the ring collection grids

3.1 Reliability assessment

At present, there are many methods of reliability assessment for collection system, and some of them have been applied to wind power system. Because of the particularity of the ring topology, it is impossible to carry out the analogy iteration like the radial structure, so this paper uses the knowledge of probability to evaluate the reliability. In this paper, the topological equivalent outage rate Q_n and the topological annual power shortage expectation E_{EENS} are used to evaluate the two indexes of reliability.

In order to calculate the reliability of the collector system conveniently, the following assumptions are made in this paper

- Assuming that the failure rate of each wind turbine is same, all of them are q_w .
- Assuming that the submarine cable distance between the wind turbines in London Array is 500 m, the outage rate q_l of each submarine cable is assumed.
- Assuming that the outage rate of each switchgear is q_s .

3.2 Complete switchgear configuration

The complete switchgear configuration of the ring topology is shown in figure 2(b). In this structure, every two WTs are connected by two switches and cables, which greatly improves the reliability of the whole topology. In this structure, there are n WTs, $(n+1)$ cables and $(2n+2)$ switches. Similarly, for the switchgear layer, one switch fault will cause one WT to stop working, while two switches fault will have 2~n operating conditions, namely, number of failed WTs $x=2,3,...,n$. To simplify the calculation, the switches at both ends of the WT are considered as a whole switch group in this paper, and the switches mentioned below default to switch combination. At this point, the failure rate of switch group q_{ss} is

$$q_{ss}=1-(1-q_s)^2 \tag{1}$$

case 1: when the WT fault, switch and cable do not affect the circuit, according to the principle of unchanging expected blocked power, only the expected power value EX_{c1} of the topology when the WTs fault occur can be considered:

$$EX_{c1}=(1-q_s)^2\cdot\sum_{k=0}^{n}C_n^k q_w{}^k(1-q_w)^{n-k}\cdot(1-q_l)^n\cdot(1-q_{ss})^n(n-k)\cdot P_n \tag{2}$$

case 2: the fault of cable and switch makes part of the WTs unable to work normally.

At this point, the switch and cable to make a specific distinction. Due to the protective effect of the switch on the cable, only one cable fault will not affect the output of the whole circuit, while any switch fault will cause the WT under its protection to be unable to work. Therefore, it is classified according to the number of fault switches:

- When there is one switch fault, one WT in the corresponding circuit will do not work. When considering WT failure, the failure rate is $q_{c21}=q_w{}^x(1-q_w)^{n-x}$. Similarly, when considering cable fault, the fault rate is $q_{c22}=q_l{}^2(1-q_l)^{n-x}$, the failure rate of the switch is $q_{c23}=q_{ss}{}^1(1-q_s)^{n-x}$. According to the probability of the opposite event, the probability of x WTs failure is

$$q_{c2}=x[1-(1-q_{c21})(1-q_{c22})(1-q_{c23})-q_{c21}] \tag{3}$$

Therefore, the equivalent output of the circuit is expected to be

$$EX_{c2}=q_{c2}(1-q_s)^2\sum_{x=1}^{n}(n-x)P_n \tag{4}$$

- There are two switches faults. Suppose there are x WTs faults in the circuit, where $x=2,3,...,n$. When considering WT failure, the failure rate is $q_{c31}=q_{c21}$. Similarly, when considering cable fault, the fault rate is $q_{c32}=q_l{}^2(1-q_l)^{n-x}$. The failure rate of the switch fault is $q_{c33}=q_{ss}{}^2(1-q_s)^{n-x}$, so the probability of the WT fault is

$$q_{c3}=x[1-(1-q_{c31})(1-q_{c32})(1-q_{c33})-q_{c31}] \tag{5}$$

Therefore, the equivalent output of the circuit is expected to be

$$EX_{c3}=q_{c3}(1-q_s)^2\sum_{x=2}^{n}(n-x)P_n \tag{6}$$

In conclusion, the equivalent stopping efficiency of the complete switch configuration can be obtained according to equation (1) as follows:

$$Q_n = 1 - \frac{EX_{c1} + EX_{c2} + EX_{c3}}{nP_n} \tag{7}$$

3.3 Partial switchgear configuration

For partial switchgear configurations, the simplest case is one WT with a switch. If you want to improve the overall reliability, you need to configure switches for more WTs. Therefore, this paper considers the situation that y ($y = 1,2,...,n-1$) WTs are equipped with switches. For the y WTs equipped with the switches, it is divided into two parts: the part with the switchgear configuration and the part without the switchgear configuration. For the unconfigured switch part, if the cable fails, the unconfigured switch part will be completely removed, with no output power, and the overall shutdown rate of the unequipped switch part is: $q_{p4} = 1-(1-q_l)^{n-y}$. Therefore, the unconfigured switch part will be regarded as the WT with capacity of $(n-y)P_n$. The configuration switchgear section is analyzed as a complete switchgear configuration. At this point, all situations are divided into two situations: partial failure of unconfigured switchgear and no fault in the unconfigured switchgear.

When the failure of part of the switchgear is not configured, a total of $1 \sim y$ WTs may be working still, which can be similar to the complete switchgear configuration. The capacity is changed from n to y, and the equivalent expected output EX_{p1} is

$$EX_{p1} = (1-q_s{}^2)P_n[\sum_{x=0}^{y-1} q_{c3}x + q_{c2}(y-1) + q_{p4}y] \cdot q_{p4} \tag{8}$$

When the non-configured switch part is fault-free , the capacity of the WTs in the circuit At this point is $(n-y)P_N \sim nP_N$, therefore, the expected output is

$$EX_{p2} = (1-q_s{}^2)P_n[\sum_{x=n-y}^{n} q_{c3}x + q_{c2}(n-1) + q_{p4}n] \cdot (1-q_{p4}) \tag{9}$$

Therefore, the Q_n is

$$Q_n = 1 - \frac{EX_{p1} + EX_{p2}}{n \bullet P_N} \tag{10}$$

4. Partial switchgear configuration optimization

Reliability is an important index for collection system of offshore wind farm, which directly affects the generation efficiency of offshore wind farm. This paper has adopted the Q_n and E_{EENS} of power shortage in topological years to evaluate. Cost is also an important indicator of the system. The increase of initial input cost will lead to investment difficulties.

4.1. Power gathering system cost analysis

The factors affecting the cost for collection system of offshore wind farms include the number of WTs, the location and voltage level of WTs, electrical equipment load, topological connection form, cable section, length and installation, etc. Among them, initial cost includes equipment cost and installation cost. Equipment cost includes: WT cost, cable cost, switchgear cost, substation cost and other equipment cost. In this paper, it is assumed that the number of WTs is fixed (the cost of WTs is fixed) and the topological wiring is well connected (the cable cost is fixed). Only the number of switches is discussed.

$$C_{total} = nC_{wc} + (n+2)C_{lc} + (2x+2)C_{sc} + C_{else} \tag{11}$$

Where, C_{total} is the total equipment cost of the power gathering system, n is the number of fans, C_{wc} is the cost of each fan, C_{lc} is the cost of each cable (assuming that each cable costs the same), C_{sc} is the cost of each switch, and C_{else} is other costs.

4.2. Overview of Pareto multi-objective optimization

In the multi-objective optimization of power system, there is competition among different objectives. At this point, the objective function cannot be measured by >, < or = in the single-objective optimization alone. At present, Pareto optimal multi-objective optimization method has been widely used in various fields [6]. It selects the optimal compromise solution according to the preferences of decision makers by weighing the relations between various variables. In the practical engineering application, it is necessary to make a choice among multiple goals, so that the overall goal will not fall into the extreme. Pareto's multi-objective optimization problem can be described as

$$\begin{cases} \min F(x) = [f_1(x), f_2(x), \cdots, f_m(x)]^T \\ s.t.\ \ g_i(x) \le 0, i = 1, 2, \cdots k \end{cases} \tag{12}$$

where $g_i(x)$ is an inequality constraint.

In this paper, the cost and equivalent outage rate are taken as objective functions, and the number of switches x is the decision variable. Combined with Pareto optimal, the multi-objective optimization in this paper can sort out as

$$\begin{cases} \min F(x) = (Q_n(x), C_{total}(x)) \\ x \in [1, n-1] \end{cases} \tag{13}$$

4.3. Multi-objective genetic algorithm based on non-inferior solution sequencing

As a heuristic algorithm, genetic algorithm can be used to solve multi-objective problems without considering the specific internal working mode of the problem, among which NSGA-II (Non-dominated Sorting Genetic Algorithm-II) algorithm is representative [7]. In this paper, NSGA-II algorithm is adopted to achieve Pareto optimization. It adopts an elite keeping strategy to retain excellent individuals directly and sort them by using crowding. The flow chart of NSGA-II is shown in fig 3.

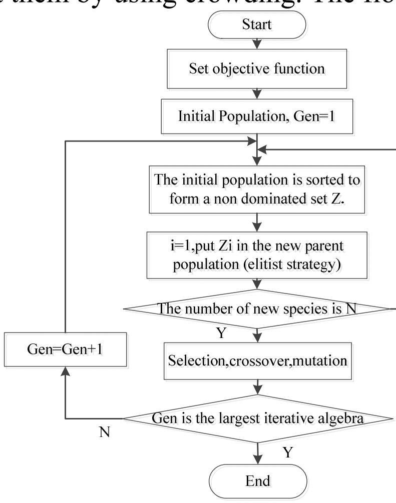


Fig 3. Schematic diagram of NSGA-II

5. The example of reliability and cost assessment

Taking London Array offshore wind farm as an example, this paper analyzes and calculates the reliability of its collection system. This paper will refer to the operation data of offshore wind farms abroad [8]. The reliability parameters of main components are shown in Table 1.

Tab 1. Reliability data of the main components.

Equipment type	Failure rate(1/yr)	MTTR(h)
Wind turbines	1.500	490
Submarine cable	0.015	1440

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5.1. The simplest switchgear configuration
For the collection system shown in Fig. 1, according to the reliability evaluation method provided in this paper, a series of 18 WTs are selected for analysis. The output power of the whole series is 64.8 MW. Comparing the complete switchgear configuration, the results are as follows:

Table 2. Reliability index of the two switchgear configuration schemes.

Schemes	Q_n	E_{EENS} $(MW \cdot h / a)$	Reduce the proportion
Partial switchgear configuration	0.0713	490	100
Complete switchgear configuration	0.0305	1440	42.77

As can be seen from Table 2, the equivalent outage efficiency of the complete switchgear configuration of the ring topology connection is significantly lower than that of the simplest partial switching configuration. Complete switch configuration is 42.77% of partial switchgear configuration, so complete switchgear configuration is obviously better than partial switchgear configuration in reliability.

5.2. The result of cost analysis
This paper only considers the equipment cost of offshore wind farm, including WT, cable and switch three aspects. For partial switchgear configuration and complete switchgear configuration, only the number of switches varies without changing wiring. The results are as follows:

Table 3. Cost of the two-switchgear configuration.

Schemes	Equipment cost(10000 yuan)	Reduce the proportion
Partial switchgear configuration	6517	100
Complete switchgear configuration	5543	85.05

As can be seen from Table 3, the cost of complete switchgear configuration is significantly higher than that of the simplest part switch configuration. We consider reducing the cost of the whole wind farm from the number of saving switches.

Since the proposed partial switchgear configuration is only one WT with switch protection, there are many configuration methods for improving reliability by adding switches to the partial switch configuration. On one hand, the increase in the number of switches will improve reliability, on the other hand, the increase in the number of switches will make the cost increase. Therefore, it is impossible to achieve the optimum between reliability and cost at the same time. Therefore, the concept of Pareto is introduced and NSGA-II algorithm is used to obtain the Pareto optimum for multi-objective functions.

5.3 The result of Pareto optimal solution
For the ring collection grids consisting of 18 WTs, the complete switchgear configuration will be adopted to reduce the Q_n when the cost is enough. To consider the cost and the equivalent outage rate, we need to use Pareto sorting to get the best compromise. The Pareto optimal solution set of some switch configurations is obtained by using NSGA-II algorithm (12) and shown by Figure 4.

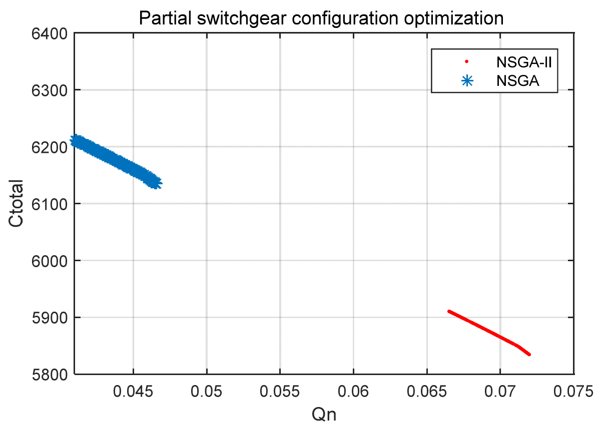

Figure 4. Pareto optimal of reliability and cost.

The NSGA-II algorithm obtains the Pareto optimal solution set of partial switchgear configuration as shown in Fig 4. The NSGA algorithm is not only slow in operation, but also easy to fall into local optimum. Therefore, the advantages of the NSGA-II algorithm can be clearly seen. Since the number of switches is regarded as a continuous real number between 1 and 17 in the Pareto sorting process, and the number of switches in the project is a positive integer, the constraint condition x=1,2,…,n-1. At this point, the optimal number of solutions can be obtained. From Figure 4, we can see that the NSGA-II optimization results are as follows: the blue thick line part in the figure, the optimal cost is stable between 6140 and 6220, the corresponding equivalent outage rate is between 0.041 and 0.047, so the number of switches is between 11 and 12; the NSGA optimization results are as follows: the red thin line part in Figure 4. The number of closed ranges is 15 to 16, which falls into local optimum. When the number of switches is 11 or 12, the trade-off between equivalent outage rate and cost will be achieved. With the difference of each string, the optimal Pareto solution set may also be different. 11 or 12 switches can make the cost and the equivalent outage rate optimal compromise, so that any objective function does not fall into extremes. In the actual construction, if the input cost is enough in the early stage, the configuration method with the largest number of switches will be adopted naturally to ensure the reliable operation of the circuit. And at the same time, the maintenance cost will be reduced to a certain extent. However, if the cost of investment is limited, the best switchgear configuration can be used to reduce investment.

6. conclusion

According to probability knowledge, reliability and cost models of complete switchgear configuration and partial switchgear configuration are established respectively. The calculation shows that the topological connection structure is unchanged, the more switches, the smaller Q_n , the higher the reliability, but the lower economy. The optimal number of switches in partial switchgear configuration is discussed by using NSGA-II algorithm, which makes the equivalent outage rate and equipment cost Pareto optimal. The results show that the switchgear configuration is an important factor affecting the reliability and cost for the collection system of offshore wind farm, and part of the switchgear configuration can be used as the main alternative in the future offshore wind farms.

Acknowledgments

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