Optimization of Electric System for Offshore Wind Farm Based on Lightweight Substation

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Abstract. The electrical system of offshore wind farms is the key to transmit the power from wind turbines to onshore power grid. With the increase of the offshore wind farms capacity and the distance from shore, the traditional centralized offshore substations is facing the challenges of capacity and construction. To solve the above problems, we propose the lightweight substation and an improved k-medoids clustering method to find lightweight substation locations, in addition, we establish the life cycle cost model of electrical system. The example of a real offshore wind farm is taken as an optimization object. The final result shows that the lightweight substation can decrease the economic costs of the offshore wind farm electrical system.

1. Introduction
In recent years, offshore wind power has developed rapidly. Currently, the capacity of large-scale offshore wind farms (OWFs) has reached up to 2.9GW and the location of the offshore wind farm off the coast can be 80 km. With the increasing power capacity of future OWFs, the optimization of the electrical system of offshore wind farms becomes more important.

Some experts have made relevant research on the electrical system of offshore wind farms. Literature [1] used the fuzzy C-means algorithm (FCM algorithm) to partition the large-scale offshore wind farm, and chose the cluster centroid of each sub-area as the installation location of substations. Literature [2] studied the transmission system between Penghu substation and Taiwan land-based substation, and considered its charging current, overload, over voltage and so on. Literature [3] took economic analysis into the redundant configuration of the main transformer based on the whole life cycle, and provided the theoretical basis for the optimal selection of the offshore wind farm transmission system.

In the electrical system of offshore wind farm, the offshore substations undertake the task of converting voltage with optimal efficiency [4]. In the above study, the electrical design of offshore wind farms is applicable for centralized offshore substations. Centralized substations have the same functions as onshore substations, but its construction cost is high, and with the increase of wind farms
capacity and the distance from shore, the installation and construction of substations are facing huge challenges.

In response to the above problems, this paper introduces a new offshore substation technology - lightweight substation. Compared with the centralized offshore substation, the substation has the decisive advantages of miniaturization and lightweight weight, which is the trend of offshore wind farm.

It is important to find the best position of offshore substations during the optimization of electrical systems. In [5], a clustering algorithm based on attribute threshold is proposed to cluster wind turbines in wind farms to determine the cluster centroid and serve as the location of offshore substations. In [6], the influence of the offshore substations location on the cost of the electrical system was considered, and the economic cost is optimized by the genetic algorithm. However, none of the above studies apply to lightweight substations. The location of lightweight substation is more flexible. It could be built not only in wind farm cluster center but in the location of wind turbine, and reduce the construction difficulty of offshore substation infrastructure.

Based on the above analysis, this paper builds a Life Cycle Cost (LCC) model applied for the offshore wind farm electrical system and proposes an improved k-medoids method suitable for site selection of lightweight substations. In addition, this paper adopts single parent genetic algorithm to optimize the topology structure of electrical system.

2. Cutting-edge technology of offshore wind farm----Lightweight-Substation

With the rapid development of offshore wind power, the fan capacity and the scale of wind farm are continuously increasing. In addition, the size and weight of substations are also increasing and the top weight exceed the single hosting capacity of vessels. These factors have bright great challenges to substation construction. In order to solve such matter, Siemens, ABB, DONG and other companies have started to design the lightweight substation for larger of fshore wind farm. The structure is shown in figure 1 and figure 2.

![Figure 1. Simple diagram of lightweight substation of ABB company.](image1)

![Figure 2. Simple diagram of lightweight substation of ABB company.](image2)

Lightweight substations could share a common foundation with wind turbines, and the installation of such substations only need the vessel with a lifting capacity of about 1000 tons.

Different from traditional centralized substations, lightweight substations are single layer structures, and employ only one large capacity transformer (traditional offshore substations often equipped with multiple transformers). The problem of reliability reduction can be solved by connecting the lightweight substations with sea cables to each other. The traditional electric system optimization model will no longer be suitable for lightweight substation, and it is necessary to establish a new electric system model for offshore wind farms.
3. Optimization model

3.1. LCC model based on centralized maritime substation

In the optimization of electric system of offshore wind farms, the centralized offshore substation location will often be selected at the cluster centroid, or selected based on the designer's experience [1,4], so it’s difficult to get the optimized results. In summary, the LCC model based on the centralized substation is shown as follows:

\[
\begin{align*}
\min C &= (C_0 + C_v + C_f) \times P_{r,\text{sum}} \\
&\quad + C_i + C_D \times P_f \\
\text{s.t. } I_{i,\text{max}} &\leq K_i I_{i,0} \\
S_{\text{im}} &= \frac{I_{i} \sqrt{I_i}}{C_i} \\
P_{\text{sum}} &\geq P_{\text{WT}} \\
(X_{\text{sub}}, Y_{\text{sub}}) &\in D_{\text{sub}} \\
C_f &= C_{\text{cable}} + C_{\text{sub}} + C_{\text{subf}}
\end{align*}
\]

Where, initial investment \( C_I \) includes the purchase cost and installation cost of submarine cable \( C_{\text{cable}} \), the purchase cost and installation cost of transformer \( C_{\text{sub}} \) and the substation construction cost \( C_{\text{subf}} \) etc. \( C_f \) is power loss, \( C_i \) is loss of operation, \( C_D \) is the operation cost of cable and transformer, \( C_D \) is the recovery cost (The value of the recycled material is considered to be offset by the cost of recycling, that is, \( C_D = 0 \)); \( P_{\text{sum}} \) is the capacity of the substation and \( P_{\text{WT}} \) is the total installed capacity of the wind farm; \( I_{\text{max}} \) is the maximum continuous load current through the sea cable \( i \), \( I_{i,0} \) is the long-term ampacity; \( K_i \) is the total correction coefficient of the long-term ampacity; \( S_{\text{im}} \) is the minimum cross-section meeting the requirement of the short-circuit thermal stability, \( I_{i,c} \) is the steady-state short-circuit current, \( t_i \) is the short circuit time, \( C_i \) is the coefficient of thermal stability, \( X_{\text{sub}} \) and \( Y_{\text{sub}} \) are the abscissa and ordinate of centralized substation respectively, \( D_{\text{sub}} \) the area outside the fan in wind farm. \( P_{r,\text{sum}} \) is the discount factor of the annual investment, \( P_f \) is the discount factor, expressed as follows:

\[
P_f = (1 + r)^{-t}
\]

\[
P_{r,\text{sum}} = [(1 + r)^{-1} - 1] / [r(1 + r)^{t}]
\]

\[
r \text{ and } t \text{ are the discount rate and useful life respectively.}
\]

The annual operating loss of the electrical system includes the submarine cable power loss during operation and the transformer operating loss [7], and its expression is:

\[
C_o = c\left[\sum_{j=1}^{n} I_j^2 R_j / t_j + \sum_{a=1}^{3} (P_{0u} t_{0u} + P_{au} \rho_a^2 \tau_{a})\right]
\]

\[
I_j = \left(\sum_{a=1}^{3} I_{e,a}^2 \cdot t_e \cdot T^{-1}\right)^{1/2}
\]

Where: \( I_j \) is the root mean square current through the high-voltage submarine cable, the expression is shown in Equation 6, \( I_e \) is the current generated by the fan at a certain wind speed, and \( t_e \) is the duration of the current, \( T \) is 8760 hours. \( c \) is the online price of offshore wind power, \( R_j \) is the resistance value, \( t_j \) is the total running time, \( P_{0u} \) is the transformer no-load loss, \( t_{0u} \) is the transformer's annual running time, \( P_{au} \) is its load loss, \( \rho_a \) is the transformer load factor, \( \tau_a \) is the year Average maximum load hours.

Maintenance cost is divided into two parts, one part is the fault maintenance of submarine cable, and the other part is the transformer maintenance costs, so the repair costs are as follows in expression:

\[
C_{\text{sub}} = \sum_{j=1}^{n} k_j c_j + \sum_{a=1}^{3} k_a c_a
\]
In the formula: \( k_j \) is the annual failure frequency of the cable, \( c_j \) is the cost of each maintenance; \( k_u \) is the annual failure rate of the transformer, and \( c_u \) is the cost of each maintenance.

### 3.2. LCC model suitable for lightweight offshore substation

Different from the centralized offshore substation, lightweight substations can share a foundation with the wind turbine. An offshore wind farm can use multiple lightweight substations instead of a traditional centralized substation. Therefore, an offshore wind farm can be divided into several sub-areas according to the number of lightweight substations. In addition, according to the reliability requirements of lightweight substations, it is also possible to interconnect several lightweight substations to improve the electrical system redundancy. The electrical system optimization model based on lightweight substations can be expressed as:

\[
\begin{align*}
\min C &= (C_0 + C_w + C_f)\times P_{\text{rew}} \\
&+ C_j + C_d \times P_v \\
\text{s.t.} & \quad I_{\text{max}} \leq K I_{\text{ro}} \\
& \quad S_{\text{min}} = \frac{I_{\text{e}}}{I_{\text{ro}}} \\
& \quad P_{\text{Tsum}} \geq \sum_{i \neq \text{WT}} P_{\text{WT}} \\
& \quad (X_{\text{sub}}, Y_{\text{sub}}) \in (X_{\text{WT}'}, Y_{\text{WT}'}) \\
C_f &= C_{\text{cable}} + C_{\text{light}} + C_{\text{sub}} + C_{\text{Hsp}} \\
(8)
\end{align*}
\]

Where, the initial investment \( C_I \) includes \( C_{\text{cable}}, C_{\text{sub}}, \) the purchase and installation cost of spare submarine cables needed for the interconnection between lightweight substations \( C_{\text{Hsp}} \), and the reconstruction costs of wind fan foundation occupied by lightweight substations; \( X_{\text{WT}} \) and \( Y_{\text{WT}} \) are the abscissa and ordinate of the fan shared base with lightweight substation \( j \) respectively.

Substations can be spared to each other by interconnection, and it reduces the possibility of all the turbines shut down in the emergent situation. High-voltage submarine cable and alternate submarine into "E" shaped arrangement, shown in Figure 3. The solid circle in the figure represent a lightweight substation, and the rectangle represents the fan group connected to each lightweight substation.

**Fig.3. A schematic diagram for connection of lightweight substations**

There are three cases in the case of cable fault or transformer fault: all wind turbines in a certain area are shut down, a part of wind turbines is shut down, and non wind turbines is shut down. Failure probability and power outage loss under different circumstances shown in Table 1:

| Power failure in a certain area | All-stop | Partial-stop | non-stop |
|--------------------------------|---------|-------------|---------|
| Probability                   | \( P_T + (1-P_T)P_HP_s \) | \( (1-P_T)P_H(1-P_s)P \) | \( (1-P_T)P_H(1-P_s)(1-P_{bi}) \) |
| Loss power                    | \( nP_0 \) | \( nP \)     | \( 0 \)  |

In the table, \( P_T \) is the fault probability of the transformer, \( P_H \) is the failure probability of high voltage submarine cable, \( P_s \) is the corresponding probability of standby submarine fault, \( P_{bi} \) is the probability of medium voltage submarine cable failure, \( n \) is the number of stoppages, \( P_v \) is the average
fan power. Therefore, we can get the expected annual power outage (E) of the wind farm in this area according to the table. The expression of annual power loss is as follows:

\[ C_F = cT_F E \]  

(10)

Where, \( T_F \) is the power failure time.

4. Solve Strategy

4.1. Lightweight Substation Location Based on Improved k-medoids Clustering Algorithm

The lightweight substation location is related to the fan coordinates and it is in a discrete range. The k-medoids clustering algorithm can be used to find a cluster centroid from the current discrete population, and the Euclidean distance from the cluster centroid to all other points is shortest. Therefore, the clustering algorithm meets the requirements of selecting the lightweight substation location in wind farms.

It is worth noting that the sample of this paper includes all the wind turbines location and onshore substation location. Medium voltage submarine cables are used between the fans and the offshore substations, and high voltage submarines are used between the offshore substations and the onshore substations. Due to the wide price variance between those two submarines, it will result in the large error if consider only the Euclidean distance. Therefore, it is necessary to improve the algorithm, and the specific model is as follows:

\[ 
\begin{align*}
ninD_F &= k_1D_H + k_2D_M \\
DH &= \sum_{i=1}^{n} d_{i \text{land}}^T \\
D_M &= \sum_{i=1}^{m} \sum_{i=1}^{j} d_{WT2s}^T 
\end{align*} 
\]

(11) \hspace{1cm} (12) \hspace{1cm} (13)

Where: \( D_H \) is the total length of the high-voltage submarine cable; \( D_M \) is the total length of the medium-voltage submarine cable; \( d_{i \text{land}}^T \) is the distance from a lightweight substation to the onshore substation; \( d_{WT2s}^T \) is the distance from the wind turbine to the lightweight substation. \( k_1 \) and \( k_2 \) are the price factors of medium and high voltage submarines, and both factors are based on the lightweight substation capacity and the number of fans in the fan string or fan ring connected to it. \( k_1 \) is the average unit price of all medium-voltage submarines, and \( k_2 \) is the price of the high-voltage submarine cable; \( D_F \) is the product of all distances and the corresponding price coefficients, and the k-medoids algorithm flow chart shown in Figure 4:
4.2. Topology Optimization Based on Partheno - Genetic Algorithm

After the site selection of substation, we adopt single parent genetic algorithm to optimize the topology. The single parent genetic algorithm does not use the crossover operator which used in the traditional genetic algorithm, and all the genetic operations are completed in a single individual. The algorithm has the merits of simple genetic operation and high calculation efficiency. In addition, it has much less strict requirements for the individual diversity of the initial population, and has no problem of "premature convergence".

Typical wind farms electrical system wiring mainly includes radial and ring: ①about the radial structure, this paper adopts the single-parent genetic algorithm and minimum spanning tree to optimize the topology. ②about the ring structure, this paper combines the single-parent genetic algorithm with the multi-traveling salesman problem to get the optimal ring topology of the electrical system.

5. Case study

5.1. Case introduction

In this paper, an offshore wind farm with the capacity of 360 MW is taken as an example. There are 100 fans with a capacity of 3.6MW, and the fans location is shown in Figure 5. The fault rate of submarine cables is 0.03 times/ (km a), the cost of repairing high voltage submarine cables is 5 million yuan, and that of medium voltage submarine cables is 1 million. The fault rate of the main transformer is 0.01. The wind farm service life is 25 years and the annual utilization hours of the fan is 2600 hours.
5.2. **Optimization Results**

In this paper, the optimization model suitable for centralized offshore substations is called the traditional station model; the optimization model suitable for the lightweight substation is called the lightweight station model. The optimization results are shown in the figures below:

![Distribution map of offshore wind turbines and onshore substations](image)

**Figure 5.** Distribution map of offshore wind turbines and onshore substations

For the traditional station model, we use the method proposed in Reference 8 to find the cluster centroid as the best location of centralized substation and optimize the electrical system topology by the method proposed in the previous section. The results are shown in Figure 6 and Figure 7, Black solid line express high voltage transmission submarine cable.

The optimization results of the lightweight station mode are shown in Figure 8 and Figure 9. Black dashed line is the standby submarine cable.

![Optimization results of radial connection under traditional station mode](image)

**Figure 6.** Optimization results of radial connection under traditional station mode.

![Optimization result of ring connection under traditional station mode](image)

**Figure 7.** Optimization result of ring connection under traditional station mode.

![Optimization results of radial connection under lightweight substation](image)

**Figure 8.** Optimization results of radial connection under lightweight substation.

![Optimization result of ring connection under lightweight substation](image)

**Figure 9.** Optimization result of ring connection under lightweight substation.
5.3. Comparison and analysis
The life cycle costs of traditional station mode and lightweight substation mode is shown in Table 4; We can find that: ① It is better to use several lightweight substations than use one traditional centralized offshore substation. In addition, the power loss of light station mode is significantly lower than that of the traditional station mode, and the reliability is higher. ② The initial investment of electrical system with ring connection is higher than radial connection. However, because the higher reliability of the ring connection, the corresponding loss of power cut loss is lower than that of the radial connection, and the total life cycle cost is lower.

Table 2 The LCC of different modes (Ten thousand yuan)

| Mode                     | Initial investment | running wastage | maintenance cost | outage loss | total life cycle cost |
|--------------------------|--------------------|-----------------|------------------|-------------|-----------------------|
| Traditional station mode (radial) | 96623              | 27735           | 15189            | 29794       | 169341                |
| Traditional station mode (ring)   | 119150             | 24239           | 17745            | 7620        | 168754                |
| Lightweight station mode (radial) | 95513              | 23469           | 18803            | 20068       | 167853                |
| Lightweight station mode (ring)   | 111192             | 21281           | 23138            | 5285        | 160896                |

The sensitivity curve reflecting the relationship between LCC and the operation time of the wind farm is shown in Figure 10. From the picture, we can find that the initial investment of the radial connection scheme is the lowest, but its life-cycle cost increases rapidly with the increase of operating years. About 10 years after operation, ring wiring costs is significantly lower than those for radial wiring. Overall, in the optimization of wind farm electrical system, the cost of using lightweight substation is lower than traditional centralized substation by 4.66%(ring structure) and 0.88%(radial structure). The advantage of the ring connection in the lightweight station mode is more pronounced than the traditional station mode.

![Fig. 10. Cumulative cost curve of offshore wind farm electrical system](image)

6. Conclusion
Comply with the trend of large-scale offshore wind farms, the paper puts forward lightweight substation and the life-cycle cost model of offshore wind farm electrical systems. In addition, the improved k-medoids clustering algorithm is used to optimize lightweight substations location. The following conclusions can be drawn by comparing the life-cycle cost of the electrical system in the traditional and lightweight station modes:
(1) For a large offshore wind farm, it is more economical to use lightweight substations than a traditional centralized substation.

(2) Although the initial investment of the offshore wind farm with ring connection is higher, it is more economical than the radial connection in terms of life cycle.

(3) With the use of a lightweight substation, the advantages of ring connection are more obvious.

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