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Combination weighting-based method for access point optimization of offshore wind farm

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Abstract

With the fast development of offshore wind power, the fluctuation of its output has an increasingly significant impact on the secure and stable operation of power system. Aiming at the large-scale offshore wind farms (OWFs) integrated, a method for selecting optimal access point is proposed. The capability of wind power accommodation, voltage stability, transmission network vulnerability and construction cost are considered as evaluation indexes. Based on the theory of information entropy and fuzzy analytic hierarchy process, taking the minimum deviation of the comprehensive weight and maximum of the compressive weight value as the optimization goal, the combination weighting model is established to determine the index weight. Simulation result of Shandong Power grid of China demonstrate the effectiveness of the proposed method for selecting the access point of the OWF.

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Keywords: Access point; Combination weighting method; Offshore wind farm; Power system

1. Introduction

In recent years, offshore wind power has developed rapidly because of energy and environmental issues. In 2020, newly installed offshore capacity in China has reached 3.06 GW, ranking first in the world (Global wind energy council, 2020) [1]. With the development of offshore wind power, larger scale offshore wind power(OWFs) will become more common (X. Zhao et al. 2015) [2]. As the scale of OWFs increases, the fluctuation of their outputs has an increasingly significant impact on the secure and stable operation of the power system (Y. Liu et al. 2016) [3]. When offshore wind farm is integrated to a different access point of power grid, the impact of it will be different, thus, selecting an optimal access point of OWF can help to improve the security and stability of power system with large-scale offshore wind power integration. The selection of optimal access point needs to consider lots of factors. In order to solve this multi-objective decision-making problem, the determination of weight is one of the

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most important problems. The methods to determine evaluation index weight are mainly divided into two categories: objective weighting method and subjective weighting method (J. Wang et al. 2017) [4]. Combining objective and subjective weighting method can improve the rationality of evaluation.

In (E. Vittal et al. 2013) [5], method based on small-signal analysis was used to identify wind farm locations for improving the stability of power system, but the factors considered were not comprehensive enough. (Y. Li et al. 2021) [6] proposed a method to determine the optimal siting and sizing of the OWF integrated with VSC-HVDC by minimizing the total investment costs, operation costs and maintenance costs of the OWFs, but the fluctuation of OWF outputs is not considered. In (X. Ma et al. 2013) [7], lots of factors were considered to select an optimal access point, but the method to determinate index weight is not scientific enough. In the research of combination weighting method, (X. Zhai et al. 2012) [8] proposed a power quality assessment method based on combination of subjective and objective weighting.

In this paper, a combination weighting-based method is proposed to select an optimal substation as the access point of OWF, which can help to solve the safety and stability issue caused by large-scale offshore wind power integration.

The remainder of this paper is organized as follows. In Section 2, the four main factors and corresponding evaluation indexes are summarized for selecting the access point. In Section 3, a combination weighting model based on the theory of information entropy and fuzzy analytic hierarchy process are employed to get the index weight. In Section 4, the proposed method is applied to select an optimal access point of Shandong power grid in the East of China. Conclusions are presented in Section 5.

2. Main factors and evaluation indexes

Wind power has fluctuation output characteristics, which makes it difficult to maintain stable outputs (H. Liu et al. 2013) [9]. With the rapid growth of wind power penetration into the grid, how to improve the capability of wind power accommodation and reduce the adverse effects resulting from wind power instability can be the main factors considered when selecting optimal access point for large-scale offshore wind power integrated. Thus, four main factors are proposed and discussed as follows.

2.1. *Capability of wind power accommodation*

The capability of wind power accommodation for access point are mainly decided by load regulation capacity and network transmission capacity. In order to calculate the maximum wind power consumption of access point, wind power accommodation capability index C_1 can be calculated as

$$C_1 = P_{j,L\,\min} + P_{j,t\,\max} - \sum_{g=1}^{G} P_{j,g\,\min} \tag{1}$$

where $P_{j,L\,\min}$ is the valley load of access point j in case of special condition, $P_{j,t\,\max}$ is the largest power that can deliver to other buses via tie-line of access point j, $P_{j,g\,\min}$ is the minimum output of the gth conventional generation unit connected to access point j. G is the number of total conventional generation units connected to access point j.

2.2. *Voltage fluctuation*

Because of the influence of natural conditions, wind power has the characteristics of randomness, volatility and intermittency. When output of OWF changes, the voltage of access area will also fluctuate due to the change of active power flow. If wind power penetration rate is high, the fluctuations of wind power may cause more serious problems. Thus, the selection of optimal access point should take it into account.

The voltage fluctuation index should indicate the fluctuation of all buses affected by offshore wind power in access area. Based on trajectory sensitivity analysis method (I. A. Hiskens et al. 1999) [10], the trajectory sensitivity index (I_{TSI}) of the voltage fluctuation caused by the change of wind power can be calculated as

$$I_{TSI} = \sum_{k=1}^{N_k} (W_k \sum_{i=1}^{n_G} (W_{bi} \frac{|U_i(t_k, P_{W0} + \Delta P_W) - U_i(t_k, P_{w0})|}{|\Delta P_W|})) \tag{2}$$

where W_k is the weight of sampling point k, W_{bi} is the weight of bus i, N_k is the total number of sampling points, n_G is the total number of bus in access area, P_{W0} is the steady output of OWF, ΔP_W is the change of wind power, $U_i(t_k, P_{W0}+\Delta P_W)$ is the voltage of bus i at sampling time t_k when the output of OWF is $P_{W0}+\Delta P_W$, $U_i(t_k, P_{W0})$ is the voltage of bus i at sampling time t_k when the output of OWF is P_{W0}.

To analyze the fluctuation of the wind power comprehensively, increasement and decrement of wind power is considered, and the result of voltage fluctuation index C_3 can be calculated as

$$C_3 = \frac{I_{TSI(\Delta P_W^+)} + I_{TSI(\Delta P_W^-)}}{2} \tag{3}$$

where $I_{TSI(\Delta P_W^+)}$ is the result of trajectory sensitivity index when wind power increases ΔP_W, $I_{TSI(\Delta P_W^-)}$ is the result of trajectory sensitivity index when wind power decreases ΔP_W.

2.3. Transmission network vulnerability

The vulnerability of access point reflects the importance and robustness of its network structure (A. Wang et al. 2011) [11]. If OWF is integrated into highly vulnerable access point, it is likely that the failure of OWF may lead to cascading failures of the power system. For the vulnerability analysis of access point, it can be considered from two aspects. One is that the higher the load rate of the tie-line connected to access point, the more vulnerable the access point, and the other is the voltage deviation of the access point under the condition of N-1 failure of the line connected to it. Grid transmission network vulnerability is introduced as follow.

For access point j, we suppose the line $I_k\,(k = 1, 2, \ldots, m_g)$ connects with bus j, and the transmission power of line I_k is P_k when the output of OWF is a steady value P_{W0}. Since the voltage class of access point for OWF is usually 220 kV, δ_k which is the weight of line I_k, is set to 0.5 and 0.2 for the 500 kV line and 220 kV line. Load rate index C_3 is calculated as

$$C_3 = \sum_{k=1}^{m_g} \delta_k \cdot \frac{P_k}{P_{k\max}} \tag{4}$$

where P_{kmax} is the most transmission power of line I_k.

Suppose that before and after the line I_k is tripped because of failure, the voltages of access point are U_{ko} and U_k, then the voltage deviation index C_4 can be calculated as

$$C_4 = \sum_{k=1}^{m_g} |U_{ko} - U_k| \tag{5}$$

2.4. Construction cost

The economic benefit of different access point is also considerable when select an optimal access point. For different access points, the construction costs are different mainly because of the length of the cable. For different access point selection schemes, the construction cost index C_5 can be calculated as

$$C_5 = \lambda_j L_j \tag{6}$$

where L_j is the straight-line distance between OWF and access point j, and λ_j indicates the bending degree of the cable length.

3. Combination weighting method

In practical multi-objective decision-making problem, all attribute values should be dimensionless. In (Y. Li et al. 2017) [12], several index dimensionless methods are introduced for decision-making problem. After transforming the raw data matrix into the standardized data matrix, the value of evaluation index is between 0 and 1, and the larger value is the better. The standardized data matrix R is

$$R = [r_{ij}]^{m\times n} \tag{7}$$

where r_{ij} is the value of ith evaluation index corresponding to jth access point after standardized, $i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$.

In order to solve a multi-objective decision-making problem, the method to determinate index weight plays a vital role for a reliable and accurate evaluation. The methods to determine evaluation index weight are mainly divided into two categories: objective weighting method and subjective weighting method. However, the objective weighting method has the advantage of strong mathematical theory, but sometimes it does not reflect the importance degree of different index based on the opinions of decision makers. The subjective weighting method relies on the attention of decision makers, but the objectivity is poor (L. Ai et al. 2019) [13]. In this paper, a combination weighting model based on the theory of information entropy and fuzzy analytic hierarchy process, with the minimum deviation of the comprehensive weight and maximum of the comprehensive evaluation value of the scheme as the optimization goal, is established to determine the index weight.

3.1. Information entropy theory

Information entropy is mainly used to describe the uncertainty of information sources, and the entropy weight method is a method for objectively evaluating index weights based on the information entropy theory. In order to solve a multi-objective decision-making problem, theory of information entropy is introduced in (J. Huang, 2008) [14].

In this decision-making problem for selecting access point with n alternative access points and m evaluation indexes, the information entropy H_i of the ith evaluation index is defined as

$$H_i = -k \sum_{j=1}^{n} f_{ij} \ln f_{ij} \tag{8}$$

$$f_{ij} = \frac{r_{ij}}{\sum_{j=1}^{n} r_{ij}}, \quad k = \frac{1}{ln\ n}, \quad i = 1, 2, \ldots, m \tag{9}$$

and we assume $f_{ij} \ln f_{ij} = 0$ for $f_{ij} = 0$.

The weight entropy $\overline{\omega}_i$ of the ith evaluating index is defined as

$$\overline{\omega}_i = \frac{1 - H_i}{m - \sum_{i=1}^{m} H_i} \tag{10}$$

3.2. Fuzzy analytic hierarchy process method

Analytic hierarchy process (AHP) was proposed by Professor T.L. Saaty which is commonly used for solving decision-making problem. However, problems such as consistency test difficulty and matrix judgment consistency are found in AHP, therefore, FAHP was proposed on the basis of AHP. Determining the weight of evaluation index based on FAHP is introduced in (L. Jiang et al. 2017) [15].

In order to solve this decision-making problem for selecting access point with n alternative access points and m evaluation indexes, the fuzzy consensus judgment matrix A is given which can be obtained by the experts' corresponding degree of evaluation index factor set.

$$A = \left[a_{ij}\right] \tag{11}$$

Among them, $0 \leq a_{ij} \leq 1$, $a_{ij} + a_{ji} = 1$ and $i, j = 1, 2, \ldots, m$. a_{ij} represents "ith index is more important than jth index", and a_i represents the ith index. It can be described by the following fuzzy scale (Table 1):

Assume that s experts are graded on the importance of A, and the evaluation value of a_{ij} is $a_{ij}^{(t)}$, $t = 1, 2, \ldots, s$, a_{ij} can be calculated as

$$a_{ij} = \sum_{t=1}^{s} \lambda_t a_{ij}^{(s)} \tag{12}$$

where λ_t is the weight of tth expert and $\sum_{t=1}^{s} \lambda_t = 1$.

Table 1. Fuzzy scale of 0.1∼0.9.

Fuzzy scale	The meaning of fuzzy scale
0.9	a_i is much more important than a_j
0.8	a_i is very important than a_j
0.7	a_i is generally more important than a_j
0.6	a_i is slightly more important than a_j
0.5	a_i and a_j are equally important
0.1∼0.4	$a_{ij} = 1 - a_{ji}$

The evaluation weight value of ith index $\overline{\overline{\omega_i}}$ can be calculated as

$$\omega_i' = \frac{1}{m} - \frac{1}{2a} + \frac{1}{ma}\sum_{j=1}^{m} a_{ij} \tag{13}$$

$$\overline{\overline{\omega_i}} = \omega_i' / \sum_{i=1}^{m} \omega_i' \tag{14}$$

where $a \geq (m-1)/2$ and a is a constant, $i = 1, 2, \ldots, m$. We can set $a = (m-1)/2$.

3.3. Combination weight

Suppose objective weight based on information entropy theory of ith evaluation index is $\overline{\omega_i}$, and subjective weight based on FAHP method of ith evaluation index is $\overline{\overline{\omega_i}}$. Assume that importance factor of objective weight is α, importance factor of subjective weight is β, the combination wight is calculated as:

$$\omega_i = \alpha\overline{\omega_i} + \beta\overline{\overline{\omega_i}} \tag{15}$$

$$\alpha + \beta = 1 \tag{16}$$

In order to make decision-making reasonable, the optimization goal is to minimize the sum of square deviations between the comprehensive weight ω_i and the objective and subjective weights $\overline{\omega_i}, \overline{\overline{\omega_i}}$, and maximize the comprehensive value of the scheme. The optimization models are constructed as

$$\min P = \sum_{i=1}^{m}\left[(\omega_i - \overline{\omega_i})^2 + (\omega_i - \overline{\overline{\omega_i}})^2\right] \tag{17}$$

$$\max Q = \sum_{j=1}^{n}\sum_{i=1}^{m} r_{ij}\omega_i \tag{18}$$

Generally speaking, it is impossible for multiple optimization objective functions to achieve their respective optimal values at the same time, there will be more or less conflicts between them, so in order to solve the above two optimization models, we can synthesize the following optimization model:

$$\min G = \sum_{i=1}^{m}\left[(\omega_i - \overline{\omega_i})^2 + (\omega_i - \overline{\overline{\omega_i}})^2\right] - \sum_{j=1}^{n}\sum_{i=1}^{m} r_{ij}\omega_i \tag{19}$$

In this case, we can construct the Lagrange function, and use the Lagrange multiplier method to solve the extreme value problem under the constraint condition of the model:

$$L(\omega_1, \omega_2, \omega_3, \ldots, \omega_m, \lambda) = \sum_{i=1}^{m}\left[(\omega_i - \overline{\omega_i})^2 + (\omega_i - \overline{\omega_i})^2\right] - \sum_{j=1}^{n}\sum_{i=1}^{m} r_{ij}\omega_i + \lambda(\alpha + \beta - 1) \tag{20}$$

where λ is a Lagrange operator, set $\frac{\partial L}{\partial \alpha} = 0$, we can get:

$$2\sum_{i=1}^{m}(2\alpha\overline{\omega_i} + 2\beta\overline{\omega_i} - \overline{\omega_i} - \overline{\omega_i})\overline{\omega_i} - \sum_{j=1}^{n}\sum_{i=1}^{m} r_{ij}\overline{\omega_i} + \lambda = 0 \tag{21}$$

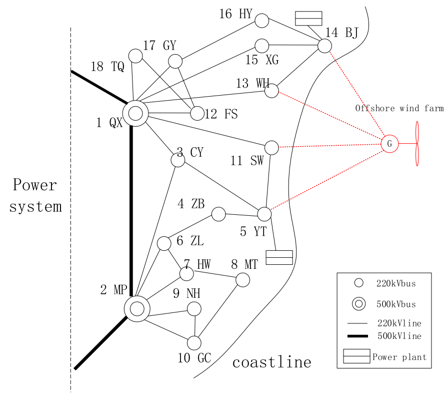

Fig. 1. Partial single line diagram of Shandong power grid.

Table 2. Index value of optional access point after standardization.

Access point	C_1	C_2	C_3	C_4	C_5
5	0.5643	0	0	0	0
11	0	0.7893	1	1	1
13	1	1	0.4813	0.7231	0.4444
14	0.6861	0.9214	0.3475	0.5543	0.9812

set $\frac{\partial L}{\partial \beta} = 0$, we can get:

$$2\sum_{i=1}^{m}(2\alpha\overline{\omega_i} + 2\beta\overline{\omega_i} - \overline{\omega_i} - \overline{\omega_i})\overline{\omega_i} - \sum_{j=1}^{n}\sum_{i=1}^{m} r_{ij}\overline{\omega_i} + \lambda = 0 \tag{22}$$

By the formula (16), (18) and (19), the value of α and β can be solved as

$$\begin{cases} \alpha = \dfrac{\sum_{j=1}^{n}\sum_{i=1}^{m} r_{ij}(\overline{\omega_i} - \overline{\overline{\omega_i}})}{4\sum_{i=1}^{m}(\overline{\omega_i} - \overline{\overline{\omega_i}})^2} + 0.5 \\ \beta = \dfrac{-\sum_{j=1}^{n}\sum_{i=1}^{m} r_{ij}(\overline{\omega_i} - \overline{\overline{\omega_i}})}{4\sum_{i=1}^{m}(\overline{\omega_i} - \overline{\overline{\omega_i}})^2} + 0.5 \end{cases} \tag{23}$$

Since α represents the importance factor of objective weight, and β represents the importance factor of subjective weight, the combination weight can be calculated by formula (15).

4. Simulation results

The proposed method is applied to Shandong power grid of China to select an optimal access point for offshore wind power. As shown in Fig. 1, it is a partial single line diagram of Shandong power system, and the OWF in Yellow Sea will be constructed near Yantai City. The capacity of OWF is 800 MW and the optional access points are 5,11,13,14 in Fig. 1, all 220 kV buses.

The dimensionless index value result is shown in Table 2. Based on the formulas given above and the expert evaluation fuzzy judgment matrix M given below, the objective weights and subjective weights are shown in Table 3.

$$M = \begin{bmatrix} 0.5 & 0.5 & 0.7 & 0.8 & 0.8 \\ 0.5 & 0.5 & 0.6 & 0.7 & 0.8 \\ 0.3 & 0.4 & 0.5 & 0.6 & 0.7 \\ 0.2 & 0.3 & 0.4 & 0.5 & 0.6 \\ 0.2 & 0.2 & 0.3 & 0.4 & 0.5 \end{bmatrix} \tag{24}$$

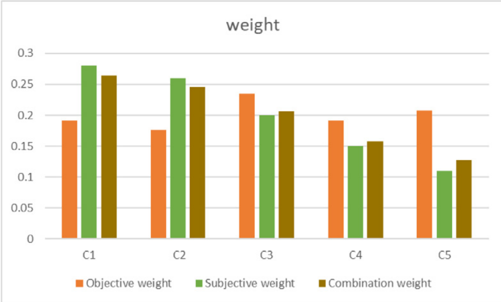

Fig. 2. Weight of evaluation index based on 3 different weighting method.

Table 3. Weights of evaluation indexes.

Type of weight	C_1	C_2	C_3	C_4	C_5
Objective weight $\overline{\omega_i}$	0.1910	0.1762	0.2347	0.1909	0.2073
Subjective weight $\overline{\overline{\omega_i}}$	0.28	0.26	0.2	0.15	0.11

Table 4. The evaluation values of each decision scheme.

Access point	5	11	13	14
Objective weighting method	0.1078	0.7719	0.7103	0.6841
Subjective weighting method	0.1580	0.6652	0.7936	0.6922
Combination weighting method	0.1490	0.6843	0.7787	0.6908

Table 5. Result of voltage fluctuation.

Access point	5	11	13	14
Average fluctuation/p.u.	0.000795	0.000648	0.000457	0.000563
Maximum fluctuation/p.u.	0.0023	0.0021	0.001	0.0016

Based on the objective weight and subjective weight, the values of α and β can be solved by Eq. (24). The result is $\alpha = 0.218$ and $\beta = 0.782$. The combination weight ω_i is as follows:

$$\omega_i = (0.2641, 0.2450, 0.2062, 0.1573, 0.1274)$$

Fig. 2. shows the weight of evaluation index based on 3 different kinds weighting method. The evaluation values of each decision scheme are shown in Table 4.

In Fig. 2, weights of evaluation indexes based on combination weighting method are between the objective and subjective weight value and there is no big difference between the results based on different weighting methods. As can be seen in Table 4, based on combination weighting method the optimal access point is bus 13, which is the same with the result based on subjective weighting method only, and slightly different with the result based on objective weighting method.

In order to verify the effectiveness of the proposed selection method, a further simulation of Shandong power system is carried out. For 4 optional access points bus 5, 11, 13 and 14, record the average and the maximum voltage fluctuation of 220 kV bus in access area when the output of OWF increase 300 WM, and the result of voltage fluctuation caused by the change of wind power is shown in Table 5.

According to the data in Table 5, when access point is bus 13, the average and maximum fluctuations of the grid voltage in the access area are the smallest, which is consistent with the calculation results of the method proposed in this paper. Considering that bus 13 also rank top on wind power accommodation capability, the result that bus 13 is the optimal access point is consistent with previous evaluation result based on combination weight method, and it proves the effectiveness of the proposed selecting method.

5. Conclusion

A combination weighting-based method is presented for selecting the optimal access point of OWF. Four main factors including wind power accommodation, voltage stability, transmission network vulnerability and construction cost are considered in the selection. This multi-objective decision-making problem is solved based on the theory of information entropy and fuzzy analytic hierarchy process (FAHP) method, and a combination weighting model is established to determine the index weight, with the minimum deviation of the comprehensive weight and maximum of the comprehensive evaluation value of the scheme as the optimization goal. Simulation results of Shandong power grid of China demonstrate the effectiveness. The proposed combination weighting-based method can get optimal access point of offshore wind farm which can improve the safety and stability of power system after the OWF integrated. The selection of several access points when multiple OWFs integrated still need further study.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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