Research on Risk Assessment Techniques of Offshore Wind Power Projects during Operation Period

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Abstract. In light of the complex operating environment and high maintenance cost of offshore wind power projects, a risk evaluation system is established in accordance with the risk's features and sources during the operation period of offshore wind power projects. On grounds of the risk evaluation system, a risk assessment method for offshore wind power projects during the operation period is put forward based on the multi-level fuzzy comprehensive evaluation method, and a specific project in the South China Sea is evaluated with the assessment model. The results showed that the risk probability is moderate to low, the consequences of the hazards are moderate, and the comprehensive risk rating is moderate for the assessed project during the operation period. It is necessary to follow the ALARP (As Low As Reasonably Practicable) principle to mitigate the risk. The risk level of offshore wind farms during the operation period can be judged using the evaluation method to provide technical support for prevention and emergency response of the accidents related to the offshore wind power projects.

1. Introduction
With the rapid development of the global economy, energy issue evolves as a problem that must not be overlooked by any country. Compared with non-renewable energy resources such as coal and petroleum, renewable green energy resources represented by wind power are developing rapidly in the world [1, 2]. According to statistics, the total wind potential that could be harnessed worldwide is about 53,000 TWh [3], and the wind power is seeing a trend of development bolstering, especially the offshore wind power projects, which has expanded by leaps and bounds in recent years. The Global Wind Report 2019 recently released by the Global Wind Energy Council (GWEC) pointed out that 2019 was an unprecedented year for the global offshore wind power industry in history, and a year witnessing the maximum increase in installed capacity in China, which together with the Asia-Pacific region will be important drivers of offshore wind power growth in the next decade. In 2019, China added record high 2.4 GW of new capacity in offshore wind power, accounting for 40% of the world's total, a year-on-year increase of nearly 51%, ranking the first in the world. China added 6.7 GW of cumulative installations in offshore wind power, representing 23% of the world's total, the third in the world [4]. Compared with onshore wind power, the offshore wind power is featured with more severe working environment, and is far costlier in the event of failure and repair. The Three-year Action Plan to Promote Workplace Safety Worldwide issued by the State Council of China in April 2020 stipulates that close attention must be paid to the risk status after changes in the utilization status and the hazard sources, dynamic assessment, adjustment of risk levels and control measures, for important links such as high-risk technologies, equipment, items, places and posts, to ensure that the safety risks are always...
kept under control. Therefore, the launching of risk assessment and emergency response management on offshore wind farms are highly relevant.

Most of the researches on offshore wind power focus on site selection [5-7], environmental effect [8-9], while the researches on risk assessment of offshore wind power projects during operation period are relatively few. Many scholars have researched the risk of offshore wind power by using correlation FMEA [10-11], risk matrix [12], SVM (support vector machine) [13] and AHP [14], etc., and achieved a lot of research results. The risk assessment methods for risk also include event tree, traffic flow theory, and quantitative analysis method. A large number of risk assessment methods are applied to ships and offshore engineering, which provide valuable reference for risk assessment of offshore wind power during operation period.

Based on the characteristics of the offshore wind farm project and the external environment, a science-based risk evaluation system is established by analyzing the risk sources of the offshore wind farm during the operation period, as exemplified by an offshore wind farm in the South China Sea. The analytic hierarchy process and fuzzy comprehensive evaluation method were adopted to analyze the risks of offshore wind farms during the operation period, and the risk levels of offshore wind farm projects were comprehensively analyzed, to provide technical support for the development and planning, policy formulation and operation management of the offshore wind power industry.

1. Risk Evaluation Indicator System

2. Risk Source Identification

Identification of risk sources is the first step of risk analysis and the key to the whole risk analysis process where the risks associated with production facilities (such as manufacturing, storage & transportation, and processing facilities) are identified. For offshore wind farm projects, the risks exist throughout the construction, operation and maintenance of the entire wind farm. The evaluation factors should be comprehensively reflected, since many factors affect the work safety of offshore wind power projects during the operation period. The risk, according to its definition, refers to the combination of the probability of an event and its consequences [15]. The risk of offshore wind power during the operation period shall be evaluated in terms of the possibility of an accident and the consequences of the hazard. The characteristics of the wind power equipment as well as the traffic volume, meteorological environment and hydrodynamic environment of the nearby seas among other factors shall be considered for the possibility of the occurrence of accidents, i.e. the probability of the occurrence; the hazard of pollutants to sensitive resources and the impact on navigation shall be chiefly studied for the consequences of the hazard which is the impact on society or the environment after the occurrence of accidents. Therefore, the risk evaluation system is a complex system covering multiple levels and many factors.

2.2. Construction of Indicator System

2.2.1. Evaluation Indicators System for Risk Possibility. The indicator system for probability of risks during the operation period of offshore wind turbines is developed (Figure 1) using the critical risk indicators screened through analysis. The first level of indicators are defined as $U = \{U_1 \text{ equipment factor}, U_2 \text{ accident}, U_3 \text{ environment}, U_4 \text{ human factor}, U_5 \text{ management risk},..., U_n\}$, and the second and third levels of indicators systems are developed in sequence. Supply vessels operators and relevant experts assign score to the risk indicators through questionnaire surveys (with the number of the participants ≥ 20), to initially determine the weight allocation of each indicator in the indicator system. The weight shown in Figure 1 are only typical examples, subject to adjustment by the evaluator according to the specific properties of offshore wind power turbines, as well as the actual environment and conditions during operation. For instance, sea ice in the natural environment is only an important indicator factor during the glacial period in the Bohai Sea, and its weight can be reduced or disregarded for other sea areas.
Figure 1. Risk probability evaluation indicators system for offshore wind power

Figure 2. Consequence evaluation indicators system for offshore wind power
2.2.2. Evaluation indicators system for the consequences of the hazard. If any accident occurs in the offshore wind power project, a large quantity of wastewater, solid waste and domestic garbage will be dumped into the sea, producing serious impact on the sensitive resources in the sea area near the project. The occurrence of such accident, if evaluated in terms of sustainable development, will impact to varying degrees on the sustainable development of society and enterprises and the effective implementation of regional environmental protection management. The improvements of the emergency response system can put the degree of hazard caused by the accident under control to an extent. The influencing factors of the consequences of hazard of offshore wind power accidents were analyzed, and the evaluation indicators system for the consequences of the hazard is finally determined (Figure 2) in reference to other research findings [16-17]. In the figure, the first-level indicator is defined as 

\[ U = \{ U_1 \text{ pollutant}, U_2 \text{ location}, U_3 \text{ Hydrodynamic}, U_4 \text{ emergency system}, \ldots, U_n \} \]

and the second-level and third-level indicators systems are developed in sequence. The risk evaluation indicators are also scored, to initially determine the weight allocation of each indicator in the indicator system. The weight shown in Figure 2 is only an example, adjustable by the evaluator according to the nature of the pollutant, the specific sea area environment and the actual emergency response capability.

3. Risk Evaluation

3.1. Determination of evaluation sets

The evaluation sets are usually expressed by \( V \), (i.e., \( V = \{ V_1, V_2, \ldots, V_m \} \)), and \( V_j \) denotes the result of evaluation. The classification of the analysis results shall be based on the nature and characteristics of the indicators, and should be not overly detailed, commonly involving 4 to 5 levels. In this research, five-level comments are used, in which the comment set of the risk probability and consequences of hazards is expressed as \( V = \{ \text{very low (VH 20)}, \text{low (L 40)}, \text{moderate (M 60)}, \text{high (H 80)}, \text{and very high (VH 100)} \} \).

3.2. Determination of membership degree

The membership degree is an effective means to realize description of evaluation indicator relative to risk levels, indicating the possibility of each factor corresponding to the element in the evaluation set. The membership degree of risk evaluation factors reflects the changing in the extent by which the evaluation criteria at different levels can be classified into a certain risk level. At present, the methods to determine the membership degree mainly include Expert Experience Method, Fuzzy Statistic Method, Dualistic Contrast Compositor Method, etc. [18-25]. In the study, the Expert Experience Method is adopted to develop a single-factor evaluation matrix, and the expert questionnaire is shown in Table 1.

Correspondence is established between the specific evaluation criteria of each indicator, which is derived from expert experience & judgment criteria, and the probability level, to realize comprehensive evaluation of the single-factor risk level.

3.3. Fuzzy comprehensive evaluation

According to the determined weight and membership degree of the evaluation indicator, a risk assessment model during the operation period of offshore wind turbines is established. The specific method is as follows.

The first fuzzy comprehensive evaluation is introduced by taking the wind power equipment factor as an example, on the basis of the evaluation indicator system. The risk rating assessment sub-set table for each second-level indicator is used to establish the membership matrix (\( R_i \)).

\[
R_i = \begin{bmatrix}
    r_{i1} & r_{i2} & r_{i3} & r_{i4} & r_{i5} \\
    r_{21} & r_{22} & r_{23} & r_{24} & r_{25} \\
    r_{31} & r_{32} & r_{33} & r_{34} & r_{35}
\end{bmatrix}
\]
Given the weight of each secondary indicator is $A_i=(A_{i1}, A_{i2}, A_{i3})$, the fuzzy comprehensive evaluation of wind power equipment is:

$$B_i = A_i \cdot R_i = (A_{i1}, A_{i2}, A_{i3}) \begin{bmatrix} r_{i1} & r_{i2} & r_{i3} & r_{i4} & r_{i5} \\ r_{i31} & r_{i32} & r_{i33} & r_{i34} & r_{i35} \end{bmatrix}$$ (2)

Where, $B_i$ is the risk evaluation matrix of wind power equipment factor, $A_i$ is the weight allocation of the second-level risk indicator in the wind power equipment factor indicator, and $R_i$ is the membership degree matrix corresponding to the wind power equipment factor indicator.

Similarly, the comprehensive evaluation result of the risk level during the operation period of offshore wind power turbines can be deduced, by calculating the risk evaluation matrix of other indicators according to this formula.

$$B = (A_1, A_2, A_3) \begin{bmatrix} B_1 \\ B_2 \\ B_3 \end{bmatrix}$$ (3)

The vector obtained from the second/third-level comprehensive evaluation results is the evaluation result of each first-level indicator risk level, and the risk level of accident probability/consequence of hazard are determined by adopting the level weighted average method.

### 3.4. Determination of risk levels

In this study, the comprehensive evaluation result of risks is determined by the possibility level and the consequence level. By referring to the *Codes for Risk Assessment of Pollution Accident by Ships* (for trial implementation), the risk level matrix (Table 1) is established to judge and evaluate the risk level of offshore supply vessels carrying dangerous goods.

| Probability × Consequence | (0, 20) | (20, 40) | (40, 60) | (60, 80) | (80, 100) |
|---------------------------|---------|---------|---------|---------|---------|
| Probability (80, 100)     | M       | H       | H       | VH      | VH      |
| (60, 80)                  | M       | M       | H       | H       | VH      |
| (40, 60)                  | L       | M       | M       | H       | H       |
| (20, 40)                  | L       | L       | M       | M       | M       |
| [0, 20]                   | VL      | VL      | L       | M       | M       |

If the risk is judged to be high or very high, it is necessary to immediately take administrative or corrective measures to reduce the possibility of accidents and control the consequences of hazards. If the risk is judged to be moderate, it is required to reduce the risk by following the ALARP (As Low as Reasonably Practicable) principle [26].

### 4. Application Example

The method is exemplified by a wind farm in the South China Sea, which is located in the southern part of the Sea, about 6nm away from the shore. The farm consists of 3 rows of 1500Kw wind turbines (33 turbines in total), and a 110Kv substation. The water depth of sea area at the level wind farm site is about 10m, and the general sea-surface wind speed is about 10.5m/s, with wind of an intensity equal to or higher than near gale occurring in 2/3 of the year. Under normal circumstances, the typhoon frequency in the sea area of the project site is 6-10 times per year, and the maximum wind speed in fifty-year return period is 51.0m/s according to relevant data analysis. In the project sea area, marine fog frequently occurs, especially for most of the time during the period January to April. Diurnal tides occur in the sea area of the wind farm site, where only one high tide and one low tide occur per day along the north-south direction. The area experiences the highest tide of 3.86m in 50 years according to statistics. Exploration and analysis revealed simple seabed geology composition mainly comprising silt soil substrate, but unstable topography and high seismic risk index. The waters near the wind farms
often witness fishing boats often come and go, which is highly likely to collide with the wind turbine piles, especially under low visibility environments. For this, conspicuous sea area warning signs have been set up around wind turbine piles and cables to reduce the possibility of accidents. Extended inspection, evaluation and maintenance has been conducted since the wind farm was put into operation, basically guaranteeing the combined implementation of regular maintenance and equipment failure elimination. At the same time, potential defects and failures of the wind turbines may be identified as early as possible by following regular inspection and maintenance plan, to reduce the probability of hidden risks. The wind power project operation and maintenance technicians are fully staffed, with high comprehensive quality, excellent professional proficiency and strong sense of responsibility, for whom relevant professional technical training will be carried out every year. They strictly observed technical regulations in work, and completed the classification and summarization of the probability of operation data and maintenance experience on time every day. With emergency equipment covering a wide range of devices, corresponding measures can be promptly taken in the event of an accident, to access the scene of the accident as soon as possible and initiate emergency response procedures to reduce the consequences of the accident to the lowest level.

According to the actual conditions such as the wind farm equipment properties, environmental conditions and management status, the fuzzy comprehensive evaluation model is used to evaluate the risks during the operation period. The evaluation results are presented in Table 2.

| Risk Factors | Initial assessment | Overall assessment | Score |
|--------------|--------------------|--------------------|-------|
| Equipment    | (0.42, 0.52, 0.06, 0, 0) | (0.29, 0.29, 0.23, 0.14, 0.05) | 47.4 |
| Accident     | (0.24, 0.20, 0.44, 0.12, 0) |                |       |
| Environment  | (0.06, 0.09, 0.285, 0.39, 0.175) | (0.06, 0.09, 0.285, 0.39, 0.175) | 56.6 |
| Human        | (0.22, 0.42, 0.36, 0, 0) |                |       |
| Management   | (0.70, 0.30, 0, 0, 0) |                |       |
| Pollutant    | (0.05, 0.375, 0.475, 0.1, 0) |                |       |
| Location     | (0.03, 0.19, 0.4, 0.3, 0.08) |                |       |
| Hydrodynamic | (0.0, 0.1, 0.25, 0.4, 0.25) | (0.12, 0.28, 0.33, 0.19, 0.08) | 56.6 |
| Emergency system | (0.41, 0.41, 0.18, 0, 0) |                |       |

From the results of the fuzzy comprehensive evaluation, it can be seen that the score for risk probability is 47.4, which is at moderate to low risk level; and the score for consequence of hazard is 56.6, which is at the moderate to high risk level, indicating that the probability of accidents in this offshore wind farm is relatively low, but consequence of hazard of accidents are relatively high. If we introduce the scores of the risk probability and consequence into the evaluation matrix, it can be found that the risk of this offshore wind farm during the operation period is moderate, which should be mitigated by following the ALARP (As Low As Reasonably Practical) principle.

5. Discussion
One drawback of the risk matrix is that it ignores the accumulation of risk. This is because the risk matrix deals with one hazard at a time. Thus, this may lead to a potential build-up of smaller risks leading to completely unacceptable risks not being addressed.

On the other hand, qualitative risk assessment methods, such as risk matrix techniques, use expert opinion to assess risk in a descriptive manner. The use of risk matrices is adopted with the help of expert advice from the maritime and shipping industries, which usually determine the degree of hazard based on their experience in the field [27-28].

6. Conclusion
The study evaluates and analyzes the risks of offshore wind farms during the operation period. According to statistical data and the actual conditions of offshore wind power in China, an evaluation
system for the possibility of accident risks and an evaluation system for the consequences of hazard are developed respectively, in which the fuzzy comprehensive evaluation method is put forward to establish the evaluation method for risk levels of offshore wind farms during the operation period. The application of the fuzzy comprehensive evaluation model to evaluating the accident risks during the operation of offshore wind farms provides reliable information for controlling critical risk sources and accident impacts in practical application, in order that suitable risk mitigation measures can be taken.

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