Meteorological risk identification and assessment of offshore wind farms

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Abstract. During the construction and operation period, an offshore wind farm is exposed to a variety of meteorological threats, which could lead to severe damages and massive financial loss. In this work, we analyse meteorological risks of offshore wind farms in the coastal areas of the south-east Jiangsu Province. Firstly, we identified the risk factors through the Delphi Method and analysis of historical data. The five major risks include typhoon, lightning, extreme temperatures, salt frog, and oceanic disasters caused directly by meteorological disasters. Then, using the Analytic Hierarchy Process (AHP), we established index module of each layer and calculated the risk value of each influence factor. After that, we established the judgement matrix and the weight of each factor. Based on that, we got the comprehensive risk value and considered it as a medium risk. According to the weighting module, we also came to the conclusion that typhoon contributes most to the meteorological disaster of offshore wind farms, with a weight of 0.3937.

1. Introduction

Wind power is one of the most eco-friendly generation methods in the world with great potential. China's installed wind capacity has doubled in each of the past four years. Its total capacity has been ranked the first worldwide since the year of 2016[1]. Coastal areas in the south-east Jiangsu Province enjoys rich wind resources. The annual generating capacity was over 1.04 million kW in 2016, more than any other province in China [2].

A Typical offshore wind farm usually operates for over 30 years after its construction [3]. In this whole period, it is exposed to a variety of meteorological threats ranging from extreme temperatures to fierce thunderstorms, which could lead to severe damages of the devices and massive loss of operators. Because of geographic and oceanic conditions in the sea, it costs much more for maintenance and repairing of offshore wind farms than that of inland wind farms. The operation company has to spend over one hundred thousand CNY per day on the specialized ships to fulfill the repairing tasks [4]. On 14 July, 2017, deflagration of cables on a booster station of a wind power farm in County Binhai, Jiangsu caused one death and a direct economic loss of over tens of millions CNY. Investigation showed that the deflagration was ignited by lightning [5]. To mitigate meteorology-related disasters and minimize financial losses, it is important to assess the meteorological risks of the offshore wind farm. Some
Chinese and overseas scholars have done some research in this field. But most of their studies focused on a certain influence factor like typhoon or lightning [6]-[10]. There are rare studies that discuss the comprehensive meteorological disasters of the wind farm. Besides, due to the fact that the offshore wind farms are located away from the land, traditional risk assessment methods are not suitable in this circumstance. So in this work, we identified the meteorological risks and established the multi-level module to calculate the risk values.

2. Risk Identification

2.1. Method of risk identification

2.1.1. The delphi method. The Delphi Method (Delphi Technique) was firstly designed by LAND Co.USA in 1946, which is also known as a correspondence survey method through anonymous expert questionnaires [11]. The following are the procedures we adopted in this study. To begin with, we selected some experts in the field of wind farm operation and meteorological sciences. Then, questionnaires and relating background information were sent to these experts. We received their responses including consensus in some aspects and some disagreements in some other aspects by some experts. According to this, we designed a second questionnaire for those who hold disagreements and received their updated feedbacks. We repeated this process till the experts reach consensus on the questionnaires, which was used for risk identification in our work. The Delphi method breaks the limit of traditional data analysis approaches, expands mentalities of decision-makers and contributes to more accurate and rational results [12]. It could provide probability estimation of likely risks in the future evolvement of a project. That’s why we adopted the method to identify and analyze the meteorological risks of offshore wind farms. Though of course theoretically we can’t prove the experts’ consensus necessarily converge to objective reality, this method did help decision-makers make better decisions on the meteorological risks.

2.1.2. Analysis of historical data. Because of specific geographical and oceanic environment of offshore wind farms, it’s important to analyze meteorological data to predict the likelihood of future disaster risks. For instance, we used historical records of temperature, typhoon, thunderstorms and lightning flashes in the wind farm site to make rational prediction of future conditions, which helps identify and mitigate meteorological risks.

2.2. Results of Risk Identification

A Typical offshore wind farm usually operates for over 30 years after its construction. In this whole period, it is exposed to a variety of meteorological threats ranging from extreme temperatures to fierce thunderstorms, which could lead to severe damages of the devices and massive loss of operators. By using the Delphi method and analysis of historical data as introduced above, we put forward with the five major meteorological risks of offshore wind farms.

(1) Typhoon

According to WMO, wind with a sustained wind velocity of L12-L13 (32.7-41.4m/s) is identified as typhoon [13]. It is a frequent meteorological disaster in China’s south-east coastal areas, which could cause a series of disastrous factors including strong winds (C11), heavy rains (C12) and storm waves (C13), posing serious threat to offshore wind turbines and facilities. The wind direction may reverse 180°in hours [13]. The wind torrent could cause forced vibration of the turbines. These are the major causes of cracks of wind turbine paddles. Historical records show that offshore wind farms of Jiangsu province has suffered heavily from typhoon-related disasters, so it is a considerable meteorological disaster to our wind farms.

(2) Lightning

Lightning is a transient but powerful discharging phenomenon in nature. Its tremendous energy, in terms of thermal effect, mechanical effect and Electro-dynamic effect could cause paddle cracks, spark-
over and insulation breakdown of generators [14]. Electronic elements may also get burnt by the lightning current. In meteorology, discharges from cloud to ground are called cloud-to-ground flashes (CG), which include positive CG flashes (C21) and negative CG flashes (C22). Discharges between clouds are called cloud-to-cloud flashes (CC), which include positive CG flashes (C23) and negative CC flashes (C24).

Wind farm turbines, with a height of 80-100m [15], are vulnerable targets of lightning flashes. The paddle are usually made of compound materials which are low in electrical conductivity and lightning endurance.

3) Extreme temperature
Though extreme temperatures don't cause physical damages to wind farms directly, experts also consider them a inducement of meteorology-related loss of offshore wind farms.

High temperatures (C31) will accelerate seawater evaporation, thus accelerating erosion of wind turbines and affiliated facilities. Besides, paddles made of high molecular materials age more quickly in hot temperature circumstances. On top of that, working with high temperature over a long period may lead to a failure of the turbine generator.

Low temperatures (C32) can cause unpredictable vibration of stalling-speed wind turbine paddles. Damping performance of the turbine’s compound materials will be affected by the low temperature, which may result in damages to the paddles and the whole turbines.

4) Salt frog
Frogs in the south-east coastal areas are usually salt frogs. Its influence depends on two factors: frogs (C41) and seawater salinity (C42). Salt frogs have a considerable chemical erosion effect on the coating of the turbines and even the turbine material itself.

5) Oceanic disasters caused directly by meteorological disasters
Meteorological phenomenon can directly incur oceanic disasters such as surge waves (C51), icing (C52) and storm surges (C53).

Surge waves are produced by wind. It can be disastrous when the wave height is above 6m[16]. It poses direct threat to turbine structure and maintenance of the wind farm. Icing is caused by low temperature, which threatens the wind facilities by pressure force and unexpected vibration. Fierce atmospheric disturbance, which includes tropical cyclones, extratropical cyclone and cold air, can lead to abnormally descending or ascending sea levels, and then surge waves follow. As direct consequence of meteorology phenomenon, these oceanic disaster compose an obvious threat to the offshore wind farm, so we take them into consideration when analyzing the meteorological risks in this paper.

3. Risk Assessment

3.1. Analytic Hierarchy Process (AHP)
The Analytic Hierarchy Process (AHP) is a structured technique for dealing with complex decisions. Rather than prescribing a "correct" decision, the AHP helps the decision makers find the one that best suits their needs and their understanding of the problem. It provides a series of options for decision-makers, who could get the finest answer through weight comparison of those options. Procedures of AHP method are listed as below [17].

(1) Model the problem as a hierarchy
The first step in the Analytic Hierarchy Process is to model the problem as a hierarchy. In doing this, participants explore the aspects of the problem at levels from general to detailed, then express it in the multileveled way that the AHP requires. As they work to build the hierarchy, they increase their understanding of the problem, of its context, and of each other's thoughts and feelings about both.

(2) Establish priorities
Once the hierarchy has been constructed, the participants use AHP to establish priorities for all its nodes. In doing so, information is elicited from the participants and processed mathematically.
(3) Synthesize these judgments to yield a set of overall priorities for the hierarchy. This would combine the investors’ judgments about location, price and timing for properties A, B, C, and D into overall priorities for each property.

(4) Check the consistency of the judgments and come to a final decision based on the results of this process.

In this work, using this method, we established a meteorological risk assessment module and calculated the impact weight of each factor.

\[
R_i = \omega_i \times r_i \tag{1}
\]

\[
R = \sum_{i=1}^{n} R_i \tag{2}
\]

\(R\) — Comprehensive meteorological risk of a offshore wind farm

\(R_i\) — Risk of target layer \(i\)

\(r_i\) — Influence value of factor \(i\)

\(\omega_i\) — Influence weight of factor \(i\)

When \(r_i = 1\), we consider the influence of this factor is low. When \(r_i = w\), we consider the influence of this factor is medium. When \(r_i = 3\), we consider the influence of this factor is high.

3.2. Module Establishment

3.2.1. Index Layers.

(1) Typhoon

Typhoon could cause a chain of disasters to the offshore wind farms, according to studies by Niu Haiyan, etc. [13], which include strong wind, heavy rainfalls and storm surges. Among them, strong wind contributes most to offshore wind farm damages. So in our work, we use it as the major factor of typhoon-caused disasters and set the risk classification as Table 1.

| Risk classification | Risk value | Risk index |
|---------------------|------------|------------|
| low risk            | 1          | 0-0.5      |
| medium risk         | 2          | 0.5-1      |
| high risk           | 3          | 1-1.25     |

(2) Lightning

Lightning flashes include cloud-to-ground flashes (CG), intro-cloud flashes (IC) and cloud-to-cloud flashes. Wind power turbines are highest structures in the waters, and the swirling paddles cause an electric field distortion, which leads to a high risk of being hit by CGs. The lightning current could cause severe physical damages to the turbines and electrical and communication network breakdown of the wind power farms. Lightning density represents the average number of lightning CG flashes occurring in a \(1\)km\(^2\) area every single year. It could help describe the likelihood of lightning activities in an area. To quantize the lightning-related risk, we analyzed the lightning density distribution in the area near the wind farm as Figure 1. Then, we set the risk classification as Table 2.
Figure 1. Lightning density in the area near the wind farm

| Risk classification | Risk value | Lightning density |
|---------------------|------------|-------------------|
| low risk            | 1          | 5                 |
| medium risk         | 2          | 5-10              |
| high risk           | 3          | above 10          |

(3) Extreme Temperature

According to China Meteorology Agency (CMA), when the temperature is above 35°C, it is called a megathermal day. The wind and solar power center of CMA classifies the temperatures below -5°C as extreme low temperatures. Both extremely high and low temperatures may pose a threat to wind farms. So, we give the risk classification as Table 3. In this work, we define the day with temperature above 35°C or below -5°C as an extreme temperature day.

| Risk classification | Risk value | Extreme temperature days |
|---------------------|------------|--------------------------|
| low risk            | 1          | <5                       |
| medium risk         | 2          | 5-10                     |
| high risk           | 3          | >10                      |

(4) Salt Frog

We analyze the salt frog risk of wind farms in terms of visibility and frequency. Wang Liping, etc. gave the frog days distribution in China’s coastal areas. According to their study, the average frog days (d) in China’s coastal areas ranges from 10-107 days in three categories: <=20 days, 20-30 days, >30 days[18]. Then, frog-related factors are shown in Table 4.
Table 4. Frog-related factors

| Visibility(km) | Frog days(d_i) | Influence index() |
|----------------|----------------|-------------------|
| <0.05          | ≤20            | 0.1               |
| 0.05-0.5       | 20-30          | 0.2               |
| <0.05          | ≥30            | 0.3               |

The frog influence factor \( T_{frog} \) can be calculated in the following equation.

\[
T_{frog} = \sum_{i=1}^{3} \omega \times d_i = 0.1 \times d_1 + 0.2 \times d_2 + 0.3 \times d_3 \tag{3}
\]

Meanwhile, for the offshore wind farms, corrosion by salt is the major threat of salt frog. So we also consider seawater salinity as an important influence factor. The salt frog related factors are listed as Table 5 and the risk classification is shown as Figure 2.

Table 5. Salt Frog related factors

| Seawater Salinity ‰ | \( T_{frog} \) | Risk grade | Risk value |
|---------------------|----------------|------------|------------|
| <31                 | <2             | Low        | 1          |
| 31-33               | 2-9            | medium     | 2          |
| ≥33                 | ≥9             | high       | 3          |

Figure 2. Discrimination matrix diagram of salt fog disaster Risk

3.2.2 Comprehensive Risk Module. Based on the discussion above, we can then calculate the comprehensive risk module of offshore wind farms. We could get a risk value ranging from 1-3 and the risk could be classified into five grades as Table 6.

Table 6. Comprehensive risk classification

| Risk grade         | Risk value |
|--------------------|------------|
| low                | 1.0 ≤ R ≤ 1.4 |
| Relatively low     | 1.4 ≤ R ≤ 1.8 |
| medium             | 1.8 ≤ R ≤ 2.2 |
| Relatively high    | 2.2 ≤ R ≤ 2.6 |
| high               | 2.6 ≤ R ≤ 3.0 |
3.3. Risk Calculation

3.3.1. Establish the judgement matrix. We established the judgement matrix using the Delphi method and carried out consistency check and weight calculation using MATLAB as shown by Table 7 and Table 8.

| Comprehensive meteorological risk | Typhoon C1 | Lightning C2 | Extreme temperature C3 | Salt frog C4 | Oceanic disasters C5 | Weight |
|----------------------------------|------------|--------------|--------------------------|-------------|----------------------|--------|
| Typhoon C1                       | 1          | 4            | 5                        | 2           | 3                    | 0.3937 |
| Lightning C2                     | 1/4        | 1            | 3                        | 1           | 1/2                  | 0.1314 |
| Extreme temperature C3           | 1/5        | 1/3          | 1/6                      | 1/5         | 0.0049               |        |
| Salt frog C4                     | 1/2        | 1/4          | 6                        | 1           | 1/3                  | 0.2018 |
| Oceanic disasters C5             | 1/3        | 3            | 6                        | 4           | 2                    | 0.2672 |

Consistency check: $\lambda_{max}=4.352$, CR=0.0667<0.1, consistency check passed

| factor                          | C1         | C2         | C3          | C4          | C5          | weight  |
|---------------------------------|------------|------------|-------------|-------------|-------------|---------|
| Strong wind C11                 | 0.5118     | 0.1314     | 0.0049      | 0.2018      | 0.2672      | 0.2015  |
| Heavy rainfall C12              | 0.0351     |            |             |             |             | 0.1390  |
| Storm wave C13                  | 0.4531     |            |             |             |             | 0.1784  |
| Positive CG lightning C21       |            |            | 0.4709      |             |             | 0.0619  |
| Negative CG lightning C22       |            |            | 0.3444      |             |             | 0.0453  |
| Positive CC lightning C23       |            |            | 0.1567      |             |             | 0.0206  |
| Negative CC lightning C24       |            |            | 0.0280      |             |             | 0.0037  |
| Low temperature C31             | 0.7315     |            |             |             |             | 0.0036  |
| High temperature C32            |            |            |             |             |             | 0.0013  |
| Frog C41                        |            |            | 0.3257      |             |             | 0.0657  |
| Salinity C42                    |            |            | 0.6743      |             |             | 0.1361  |
| Surge wave C51                  |            |            |             | 0.3346      | 0.0894     |         |
| Ice C52                         |            |            |             | 0.2439      | 0.0652     |         |
| storm surge C53                 |            |            |             | 0.4215      | 0.1126     |         |
3.3.2. Comprehensive Risk Value.

Table 9. Risk value of each factors

| factor                  | r_i | ω_i | R_i |
|-------------------------|-----|-----|-----|
| Strong wind C11         | 2   | 0.2015 | 0.4030 |
| Heavy rainfall C12      | 1   | 0.1390 | 0.1390 |
| Storm wave C13          | 2   | 0.1784 | 0.3568 |
| Positive CG lightning C21| 3   | 0.0619 | 0.1857 |
| Negative CG lightning C22| 3   | 0.0453 | 0.1359 |
| Positive CC lightning C23| 3   | 0.0206 | 0.0618 |
| Negative CC lightning C24| 3   | 0.0037 | 0.0111 |
| Low temperature C31     | 1   | 0.0036 | 0.0036 |
| High temperature C32    | 1   | 0.0013 | 0.0013 |
| Frog C41                | 2   | 0.0657 | 0.1314 |
| Salinity C42            | 2   | 0.1361 | 0.2722 |
| Surge wave C51          | 1   | 0.0894 | 0.0894 |
| Icing C52               | 1   | 0.0652 | 0.0652 |
| storm surge C53         | 1   | 0.1126 | 0.1126 |

We got the risk value of each factors in Table 9, and according to Equation (4), the comprehensive risk of the wind farm is 1.969, right between 2.2 and 2.6. So we consider it as a medium risk.

\[ R = \sum_{i=1}^{14} R_i = \sum_{i=1}^{14} \omega_j \times r_j = 1.969 \] (4)

4. Conclusion

In this work, meteorological risks of offshore wind farms along Jiangsu coastal areas are identified through the Delphi Method and analysis of historical data. The five major risks include: (1) Typhoon, a frequent meteorological disaster in China’s south-east coastal areas, which could cause a series of disastrous factors including strong winds, heavy rains and storm waves, posing serious threat to offshore wind turbines and facilities. (2) Lightning, including cloud-to-ground flashes (CG) and cloud-to-cloud flashes (CC), whose tremendous energy could cause paddle cracks, spark-over and insulation breakdown of generators. (3) Extreme temperatures, which could be an inducement of some forms of damages such as unpredictable vibration of stalling-speed wind turbine paddles and accelerated erosion. (4) Salt frog, whose influence depending on frogs and seawater salinity. (5) Oceanic disasters caused directly by meteorological disasters, such as surge waves, icing and storm surges.

Then, using the Analytic Hierarchy Process (AHP), we established index module of each layer and calculated the risk value of each influence factor. After that, we established the judgement matrix and the weight of each factor. Based on that, we got the comprehensive risk value of the offshore wind farms along Jiangsu coastal areas and considered it as a medium risk according to the module. As is seen from the weight analysis, typhoon contributes most to the meteorological disaster of offshore wind farms, with a weight of 0.3937, followed by oceanic disasters caused directly by meteorological phenomenon, with a weight of 0.2672. Compared with other factors, the wind farm suffers least from the extreme temperature, whose weight is 0.0049, approximately one eightieth of that of typhoon.

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