Research on Output Scenarios of Offshore Wind Power Considering Characteristics of Marine Weather

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Abstract. Accurate modeling of stochastic wind power output is one of the key links in the optimal operation of power systems with large-scale wind power. According to the output characteristics of offshore wind farms, a data-driven method that models offshore wind power output scenarios is proposed in this paper. This method takes full account of the marine climate characteristics to study the offshore wind farm output data seasonally and identifies the main climatic elements affecting the output of offshore wind farms through correlation analysis. Meanwhile, the evaluation index of output characteristics is established. In order to reflect the influence of marine climate on the output of offshore wind farms, the climatic factors are used as an indicator to distinguish different weather. Accordingly, the output scenarios of offshore wind farms in extreme and non-extreme weather are determined, and the corresponding probability calculation method is proposed.

1. Introduction

In recent years, energy exhaustion and environmental pollution are becoming more and more serious. Wind power generation has the characteristics of non-pollution and sustainability, and its application prospect is very broad. Due to the limitation of land resources and wind energy resources, large wind farms are gradually located in remote areas or offshore areas far away from power nodes [1]. Compared with land wind resources, offshore wind energy resources have many features [2,3,4], such as the lower fluctuation of offshore wind power output, stronger degree and probability of anti-peak regulation than onshore wind power, close relationship to marine meteorology, obvious seasonal characteristics of power output. And tropical cyclones will bring both advantages and disadvantages to offshore wind power generation [5].

The current wind farm output modeling method is mainly aimed at land wind farms, which cannot fully adapt to the modeling of offshore wind farms. The various properties of offshore wind power bring great challenges to the power system simulation, and the establishment of an output model that can accurately reflect the output characteristics of offshore wind power is the premise to realize the optimization of large-scale offshore wind power accommodation and power system planning.
Ordinarily, for offshore wind power, the wind power output model used in the existing system planning field can be divided into physical model and typical scenario model. The physical model based on the external characteristic of the wind turbine, which is the relationship between the power output and wind speed, it also should consider the wake effect and various losses to generate the output curve of the wind field [6,7]. Reference [8] proposed a modeling framework which can simulate turbine wakes and power losses in wind farms, using the large-eddy simulation technique with blade element theory. Reference [9] proved that the Jensen's wake model is a good choice to solve the wind farm layout problem due to its simplicity and a relatively high degree of accuracy. The physical model can calculate the wind output according to the wind speed, which is suitable for the condition with insufficient historical output data. However, this kind of model ignores the time series characteristics of wind power output. The data-driven typical scenario model makes up for the deficiency of the physical model. The time-series output curves needed in this method can be generated by the historical output curves or simulated by the method of autoregressive moving average model and Markov chain principle statistics [10]. Reference [11] proposed a scenario-based modeling methodology able to capture the main features of wind, which can be used to reduce size of data sets in practical applications without using any simplifying assumption. The above literature has conducted enough research on the modeling methods of land wind power, but it is difficult to directly apply them to the offshore wind power modeling which has more complex output characteristics. Aiming at the engineering requirements of large-scale offshore wind power operation simulation, this paper studies the modeling method of typical scenarios of offshore wind power output, which is suitable for the characteristics of offshore wind energy resources. Considering all kinds of weather in the marine and taking the weather as the division basis of output scenarios, the output models of the offshore wind farm in extreme weather and non-extreme weather conditions are constructed. The work done by this paper can be applied to the operation simulation of power system planning with large-scale offshore wind power connected to the power grid.

2. Characteristic index of marine weather

To construct the data-driven typical output scenario, the output curves of the offshore wind farm and the data of climatic elements are required. The characteristic indices of marine weather include the monthly average output of offshore wind farm and the marine climatic elements.

The output characteristics of offshore wind farms are largely affected by the marine monsoon climate. Therefore, to improve the accuracy of the selection of typical output scenarios, the output characteristics of the offshore wind farm should be analysed. Then divide the output curves into \( S \) seasons according to the monthly average output. The specific description is shown as below.

\[
P' = \{P^m | P^m \in R^s\}
\]

where, \( P' \) is the set of offshore wind farm output curves in the \( s \)-th season; \( P^m \) is the set of offshore wind farm output curves in the \( m \)-th month; \( P^m_{avg} \) is the monthly average output of \( m \)-th month; \( R' \) is the monthly average output range of the \( s \)-th season.

Marine climatic elements include wind speed \( v \), atmospheric pressure \( p \), temperature \( T \), precipitation \( R \), relative humidity \( U \), and cloud cover \( C \). By conducting correlation analysis, the climatic elements with high correlation are selected as the characteristic index of marine weather, which affect the \( s \)-th season output of offshore wind farm. When conducting the multiple regression analysis of output data and climatic elements, Pearson correlation coefficient is used. The Pearson correlation coefficient between the output data \( x \) of the offshore wind farm and the climatic element \( y \) in the \( s \)-th is shown as follows:

\[
R_{xy} = \frac{\sum_{i=1}^{s}(x_i - \bar{x})(y_i - \bar{y}) \cdot \left( \frac{\sum_{i=1}^{s}(x_i - \bar{x})^2 \sum_{i=1}^{s}(y_i - \bar{y})^2}{\sum_{i=1}^{s}(y_i - \bar{y})^2} \right)^{-0.5}}{\sum_{i=1}^{s}(x_i - \bar{x})^2}
\]

where, \( \bar{x} \) and \( \bar{y} \) are the sample mean of the output data \( x \) and the climatic element \( y \).
The correlation coefficient $R_{xy}$ is positive means that the output $x$ is positively correlated with climatic element $y$, and $R_{xy}$ is negative means that the wind output $x$ is negatively correlated with climatic element $y$. The closer the absolute value of correlation coefficient $R_{xy}$ is to 1, the stronger the correlation is, the closer it is to 0, the weaker the correlation is. Take the climatic element $y$ whose Pearson correlation coefficient $R_{xy} > 0.4$ as the characteristic index of marine weather $\{G_1, G_2, \cdots, G_i\}$, which affects the $s$-th season output of the offshore wind farm.

3. Data-driven typical output scenario model of offshore wind power
Considering the influence of marine weather on the offshore wind power output, this paper established the key output scenario of offshore wind power, namely the typical output scenarios of offshore wind power in non-extreme and extreme weather.

3.1. Typical output scenarios of offshore wind in non-extreme weather
The daily average output $P_{avg}$ and daily peak-time output $P_{peak}$ in non-extreme weather in $s$-th season are taken as the characteristic parameters of these typical scenarios, which affect the start-up capacity of conventional power units of the system. To determine the typical output scenarios and their corresponding probabilities in non-extreme weather in $s$-th season, the following steps are included:

a) Based on the daily peak-time output $P_{peak}$, the daily output curves $P_s$ in non-extreme weather in $s$-th season are sorted according to $P_{peak}$ from small to large;

b) Considering that the minimum wind output is too low, given the confidence level $\alpha \in (0,1)$ to screen the daily output curves $P_s$, to make sure that peak-time power output is not less than $P_{peak, \alpha}$ with the probability of exceeding $\alpha$. The screened curves form the set $P'_s$;

$$P'_s = \{ P_s \mid f \left( P_{peak} \geq P_{peak, \alpha} \right) > \alpha \} \quad (3)$$

c) In order to ensure the representativeness of the selected scenarios, the power curves should have a certain electricity benefit. Therefore, given the output level $\varepsilon \in (0,1)$ to screen the daily output curves from set $P'_s$. The screened curves are recorded as the set $P''_s$, which can ensure that the daily average output $P_{avg}$ in the research period is not less than $\varepsilon$;

$$P''_s = \{ P''_s \mid P_{avg} \geq \varepsilon \} \quad (4)$$

d) Considering the influence of marine weather on the output of offshore wind farm, take the characteristic index of $s$-th season marine weather as the evaluation basis of similar weather. For the non-extreme marine weather $W = \{G_1, G_2, \cdots, G_i\}$, considering the situation that the wind output is not enough in peak-time and reserving enough reserve capacity, select the daily output curves from set $P''_s$ with the minimum peak-time output $P'_{peak}$ as the typical output scenarios of the $s$-th season under the non-extreme weather $W$ and confidence level $\alpha$. The selected curves form the set $P''_{s,W}$:

$$P''_{s,W} = \{ P''_s \mid \min \left( P'_{peak} \right) \} \quad (5)$$

e) The probability of typical output scenario can roughly evaluate the output level of offshore wind farm under weather $W$ and confidence level $\alpha$. The smaller the probability is, the more the offshore wind farm is affected by the type of weather $W$. It is calculated as follows:

$$f'_{\alpha,W} = N_s^{-1} \quad (6)$$

where, $f'_{\alpha,W}$ is the probability of typical output scenario under weather $W$ and confidence level $\alpha$; $N_s$ is the number of daily power curves in set $P''_s$ under weather $W$. 


3.2. Typical output scenarios of offshore wind in extreme weather

The output of offshore wind farm is close to full capacity in extreme weather, thus the daily average output $P_{avg}$ is taken as the characteristic parameters. To determine the typical output scenarios and their corresponding probabilities in extreme weather in $s$-th season, the following steps are included:

a) Based on the daily average output $P_{avg}$, the daily output curves $P'$ in extreme weather in $s$-th season are sorted according to $P_{avg}$ from small to large;

b) In order to ensure the electricity benefit of the selected scenarios, given the confidence level $\beta \in (0,1)$ to screen the daily output curves $P'_s$, to make sure that the daily average output $P_{avg}'$ is not less than $P_{avg,\beta}$ with the probability of exceeding $\beta$:

$$P'_s = \left\{ P' \mid f\left(P_{avg} \geq P_{avg,\beta}\right) > \beta \right\}$$  \hspace{1cm} (7)

c) Take the characteristic index of $s$-th season marine weather as the evaluation basis of similar extreme weather. For the extreme marine weather $W = \{G', G', ..., G'\}$, select the daily output curves from set $P'_s$ with the maximum daily average output $P_{avg}'$ as the typical output scenarios of the $s$-th season under the extreme weather $W$ and confidence level $\beta$. The selected curves form the set $P'_{s,W}$:

$$P'_{s,W} = \left\{ P'_s \mid \max(P_{avg}') \right\}$$  \hspace{1cm} (8)

d) The probability indicates the occurrence probability of the highest average daily output of offshore wind farm under extreme weather $W$ and confidence level $\beta$, which can roughly evaluate the output level in extreme weather. It is calculated as follows:

$$f_{s,W}^{\beta} = N_{p}^{-1}$$  \hspace{1cm} (9)

where, $f_{s,W}^{\beta}$ is the probability of typical output scenario under weather $W$ and confidence level $\beta$; $N_{p}$ is the number of daily power curves in set $P'_s$ under weather $W$.

4. Case study

4.1. Basic data

The case is based on the annual power output data of a large offshore wind farm in Southeast China in 2019. The climatic elements include wind speed, temperature, precipitation and cloud cover. Figure 1 shows the monthly average output distribution of the wind farm. According to the marine monsoon characteristics of the sea area where the offshore wind farm is located, the power output data and the climatic element data are divided into 4 seasons.

![Figure 1. Monthly average output of the offshore wind farm](image-url)
The power output data $P$, wind speed $v$, temperature $T$, precipitation $R$ and cloud cover $C$ of the offshore wind farm are analyzed by multiple regression analysis. The correlation coefficients between wind farm output and four climatic elements are shown in Table 1. From the table we know, only wind speed $v$ is taken as the characteristic index of marine weather, and the corresponding weather classification are breeze wind, strong wind, gale wind and extreme weather.

**Table 1.** The correlation coefficients between wind output and climatic elements

|   | $S$  | $v$  | $T$  | $R$  | $C$  |
|---|------|------|------|------|------|
| 1 | 0.497| -0.135| 0.073| 0.135|      |
| 2 | 0.473| -0.189| 0.137| -0.014|      |
| 3 | 0.693| -0.044| 0.148| 0.206|      |
| 4 | 0.500| -0.215| -0.042| 0.164|      |

4.2. Results

Based on the daily peak-time output $P_{\text{peak}}$, given the confidence level $\alpha = 0.9$ and the output level $\varepsilon = 0.2$, the daily output curves of the offshore wind farm in $S$ season in non-extreme weather is screened and the set $P^*$ is yielded. Then the curves with the minimum daily peak-time output are selected as the typical output scenarios. The results as shown in Figure 2(a)-(c). These scenarios represent the characteristics of the wind farm in each season, and they can be applied in system dispatching to avoid the shortage of power supply at peak-time.

![Figure 2](image-url)

**Figure 2.** (a) The scenarios in breeze wind weather; (b) The scenarios in strong wind weather; (c) The scenarios in gale wind weather; (d) The scenarios in extreme weather;

Based on the daily average output, given the confidence level $\beta = 0.95$, the daily output curves of the offshore wind farm in $S$ season in extreme weather is screened. Then the curves with the maximum daily average output are selected as the typical output scenarios. The results are shown in Figure 2(d). The daily average output of each curve in the figure is very high, which reflects the situation that the offshore wind farm is close to full capacity under extreme weather.
The Figure 3(a)-(d) shows the case of another offshore wind farm, which use the same parameters as the previous case. The second wind farm is located in the open sea area, and there is no mainland blocking the wind. So comparing the typical output scenarios of the two offshore wind farms, we can find that the second one is more abundant in wind energy resources. This can prove the effectiveness of our method.

![Figure 3](image_url)

**Figure 3.** (a)The scenarios in breeze wind weather; (b)The scenarios in strong wind weather; (c)The scenarios in gale wind weather; (d)The scenarios in extreme weather;

5. **Conclusion**

Considering the marine monsoon climate which has a significant impact on offshore wind power generation, this paper divides the data into S seasons, and accurately identifies the weather characteristic indices through correlation analysis which improves the accuracy of the scenarios. The study provides a method to select typical output scenario and calculate its probability for the offshore wind farm. The scenarios can reflect the output characteristics of the offshore wind farm, and can be used for the operation simulation and benefit evaluation of power systems with high proportion of offshore wind power connected in the future. At the same time, this paper fully considers the huge impact of various kinds of marine weather on the output of wind farm, and creatively proposes the selection method of typical output scenarios in extreme and non-extreme marine weather. Applying these scenarios to system operation simulation can further guarantee the security and stability of power grid and improve the absorption rate of offshore wind power.

6. **References**

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