Output characteristic analysis and delivery line capacity exploration of large-scale offshore wind power

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Abstract. Offshore wind power slightly differs from onshore wind power in output characteristics due to the impact of wind resources and maritime environment. This paper analyses the characteristics of offshore wind power from the perspectives of resource characteristic, output characteristic and operational characteristic, illustrates the matching between offshore wind power and regional loads, and finally explores a capacity design strategy on a delivery line of offshore wind power based on the abandonment of wind power, to provide a reference for optimization of regional wind power layout and reduction of costs arising from new energy consumption.

1. Introduction
While supplying low-carbon and environmentally-friendly power in the areas concerned, the offshore wind power often leads to multi-mode operation of the power system as a result of large-scale access and high output, increasing the operating risks[1]. It is necessary to study the characteristics and delivery of offshore wind power. The Reference [2] shows a statistical characteristic evaluation index system for conventional wind power. The Reference [3] analyses the statistical characteristics of outputs of offshore wind farms based on the operation simulation technology. The Reference [4] analyses the impact of large-scale wind power on peak regulation by simulating the time series curve of wind power output. The References [5-7] propose the credible capacity of wind power in a power system from the perspective of substation of a conventional generator set with wind turbine generator system (WTGS). The References [8-9] give two methods for randomly generating wind speed time series.

Given the large-scale integration of offshore wind power, this paper analyses the method of simulating offshore wind power output, presents the output characteristics of offshore wind power, and studies their coupling relationship with loads. In addition, this paper preliminarily explores the strategy for capacity design of the delivery line of offshore wind power. On the premise of meeting the consumption needs of offshore wind power, this strategy is helpful to improve the system economy and provides a reference for regional planning.

2. Characteristics of offshore wind power
With the advancement of offshore wind power and increasing scarcity of land resources, offshore wind power is developed rapidly. The study on offshore wind power characteristics can provide a basis to develop a reasonable operational strategy for the power system and increase the consumption of offshore wind power. This paper divides offshore wind power characteristics into three categories:
2.1. Wind power output characteristic

2.1.1. Volatility. Volatility is the most typical natural characteristic of wind power output, expressed as \( \rho \% \). The wind power output volatility refers to the ratio of wind power output variation to rated capacity within a specific period:

\[
\rho \% = \frac{P(t+T) - P(t)}{S_{\text{wind}}} \times 100\%
\]

Where, \( P(t+T) \) is the wind power output at the time \( t+T \); \( P(t) \) is the wind power output at the time \( t \); and \( S_{\text{wind}} \) is the rated capacity of the WTGS.

The wind power variation is often positively correlated with wind speed fluctuations. The wind speed change greatly as a result of obstacles on the undulated land, and remains relatively stable on the flat sea level where the resistance to wind is small. Thus, offshore wind power is generally less volatile than onshore wind power.

2.1.2. Reliability. The unplanned outage rate \( \mu_{\text{un}} \) is used as an index reflecting the reliability of offshore wind power in this paper. It refers to the ration of annual unplanned outage hours to total outage hours, and is primarily related to the climate of the sea area where the WTGS is located as well as the manufacturing level of the WTGS itself. The unplanned outage rate is calculated by the formula below:

\[
\mu_{\text{un}} = \frac{H_{\text{un}}}{8760}
\]

Where, \( H_{\text{un}} \) is the number of unplanned outage hours in a year.

Compared with the terrestrial environment, the marine environment is even worse. Especially in the bad weather such as typhoon, offshore wind power is often subject to abnormality, which is likely to cause large-scale outage and great impact on the power system. Moreover, the difficulties in and costs of operation and maintenance of offshore wind power are much higher than those of onshore wind power, as a result of harsh conditions and poor accessibility. This is one of critical factors restricting the development of offshore wind power[10,11].

2.2. Wind power coupling characteristic

The impact of offshore wind power on a power system is associated with the WTGS capacity and grid scale on the one hand, and with the wind power-load coupling characteristics on the other hand. Wind power coupling characteristics are represented by the scale and peak regulation.

2.2.1. Scale characteristic. For a specific region, the impact of offshore wind power usually varies from its integration scale. In order to accurately evaluate the impact of wind power integration on a power system, the penetration rate is adopted in this paper to represent the scale of offshore wind power in region. It refers to the ratio of wind power to maximum load:

\[
P_s(t) = P(t)/P_l(t)
\]

Where, \( P(t) \) is the load at the time \( t \).

2.2.2. Peak regulation characteristic. In order to analyse the impact of the integration of offshore wind power on a local power system, the variation of peak valley difference is used in this paper to represent the peak regulation characteristics of wind power. The grid-connected wind power is regarded as a negative load, which is superimposed with the actual load to obtain the net load. Then
the variation of peak valley difference of the net load corresponding to that of the original load is calculated, thereby obtaining the peak regulation characteristics of wind power.

Figure 1. Original load and net load of a typical day.

In the typical daily load curve in Figure 1, the variation \( \Delta D_{pv} \) of peak valley difference before and after wind power integration is:

\[
\Delta D_{pv} = D'_{pv} - D_{pv} \\
D_{pv} = P_{\text{max}} - P_{\text{min}} \\
D'_{pv} = P'_{\text{max}} - P'_{\text{min}}
\]

(4)

Where, \( D_{pv} \) and \( D'_{pv} \) are the peak valley difference of the original load and that of the net load, respectively; \( P_{\text{max}} \) and \( P_{\text{min}} \) are the maximum and minimum original load, respectively; and \( P'_{\text{max}} \) and \( P'_{\text{min}} \) are the maximum and minimum net load.

Apparently, a positive value of \( \Delta D_{pv} \) means that wind power has negative effects on peak regulation of the power grid of the area where wind power is integrated; otherwise, the wind power has positive effects on peak regulation.

2.3. Efficiency characteristic

The efficiency characteristic of wind power refers to the utilization rate of the WTGS and that of wind energy by the WTGS. As a measure of the operation and technical economy of a power plant, the efficiency characteristic directly affects the costs of the power plant and even power system. It involves the utilization rate of the WTGS and wind energy, respectively.

2.3.1. WTGS utilization rate. In this paper, the WTGS utilization rate is represented by annual utilization hours \( H_{\text{wind}} \), i.e. WTGS running hours corresponding to the rated capacity during the actual operation.

\[
H_{\text{wind}} = \left( \frac{Q_{\text{wind}}}{S_{\text{wind}}} \right) \times 8760
\]

(5)

Where, \( Q_{\text{wind}} \) is the actual annual wind power output in a year (or a statistical period).

The annual utilization hours is greatly affected by local wind resources. A small number of annual utilization hours indicate the low utilization rate of WTGS and high costs of installation.

2.3.2. Wind energy utilization rate. The abandoned wind power rate is applied in this paper to represent the wind energy utilization rate. It refers to the ratio of the abandoned wind power to theoretically available power in a statistical period.

\[
r_{\text{car, wind}} = \frac{Q_{\text{car, wind}}}{Q_{\text{car, wind}} + Q_{\text{wind}}}
\]

(6)

Where, \( Q_{\text{car, wind}} \) is the abandoned wind power in the statistical period, and \( r_{\text{car, wind}} \) is the rate of abandoned wind power in the statistical period.

3. Case analysis

The municipal power grid of a coastal region in East China was taken as an example. The offshore wind power there is located to a nearby 220kV grid for local consumption. The excess wind power is
transmitted to be consumed within the province concerned. The annual load curve of the above-mentioned municipal grid in 2016 is shown in Figure 2. It can be seen that the load significantly declines during the Spring Festival and rises in summer.

![Figure 2. Annual load curve of a municipal power grid.](image)

As planned, the consumption of offshore wind power there will be approximately 2.05 million kilowatts in 2020. The data was collected on the wind speed probability distribution, time series autocorrelation coefficient of the wind speed and historical curves of the wind farm. Then the output curve of offshore wind power in that year was obtained via the wind farm operation simulation model based on the random difference equation. Taking into consideration of the corresponding load increase and needs of local loads, The output curve of wind power output deduction minus local load is shown in Figure 3.

![Figure 3. Delivery curve of offshore wind power.](image)

The approximate probability density of output change rate of offshore wind power at different scales is based on the volatility analysis of the offshore wind farm in a year, as illustrated in Figure 4.

![Figure 4. Probability distribution of the rate of annual offshore wind power change.](image)
The maximum volatility of the wind farm within 5 min is 42.09%, for which the probability of 5% or less is 98.28%; the maximum volatility within 15 min is 68.91%, for which the probability of 5% or less is 90.57%; the maximum volatility within 60 min is 73.47%, for which the probability of 5% or less is 87.17%. It can be seen that, with the time scale increasing, the distribution becomes “wider and shorter”, indicating that fluctuations are intensified. The peak regulation characteristics were analyzed in combination with load data, and the probability distribution of variation of peak valley difference after wind power connection is shown in Figure 5. As shown in this figure, there are obvious adverse effects on peak regulation after offshore wind power is connected, especially in spring and autumn.

![Figure 5. Probability distribution of the variation of peak valley difference.](image)

According to the statistics, 4.44 billion kWh of offshore wind power is available for delivery, the delivery power is 1.419 million kilowatts, and the maximum power received is 0.9 million kilowatts. The statistical analysis of the delivery curve shows that the probability of the delivery power greater than 1.08 million kilowatts is only 5%, as shown in Figure 6. The statistics indicates that the delivery power exceeding 1.08 million kilowatts only accounts for 1.4% of the annual output of offshore wind power.

![Figure 6. Probability distribution of delivery offshore wind power.](image)

A delivery line of appropriate capacity can be planned and constructed based on the acceptable rate of abandoned wind power. For instance, assuming that the maximum capacity of the delivery section is 1.08 million kilowatts, the annual delivery power is 4.31 billion kWh except for local load needs, the maximum annual delivery power will be 1.08 million kilowatts, and the maximum received power will be 0.9 million kilowatts. The statistical information of the delivery section is shown in Table 1.

| Parameters                        | Values |
|-----------------------------------|--------|
| Forward capacity ($10^4$ kW)     | 108    |
Reverse capacity (10^4 kW) 108
Transmission capacity (10^8 kWh) 43.87
Average section power flow (10^4 kW) 50
Forward maximum power flow (10^4 kW) 108
Reverse maximum power flow (10^4 kW) -90
Utilization rate 0.46
Utilization hours 4061

| Hours require to reach | 100% power flow | 95% power flow | 90% power flow | 85% power flow |
|------------------------|-----------------|----------------|----------------|----------------|
| Hours                  | 755             | 1,038          | 1,258          | 1,410          |

Under this circumstance, the amount of annual abandoned offshore wind power is 81.1 million kWh, the curtailed rate thereof is 1.4%, and the distribution is as shown in Figure 7.

**Figure 7.** Monthly abandoned offshore wind power.

### 4. Conclusions
The offshore wind power output has significant seasonal characteristics, usually high in spring and winter and low in summer. The wind power also fluctuates in various seasons, a little in spring and winter with high wind power output, and drastically in summer and autumn with low wind power output. The narrower the time scale, the more apparent the wind power fluctuations are. The penetration rate of offshore wind power also changes greatly in four seasons, which reaches the maximum in spring and winter and minimum in summer. From the perspective of peak regulation characteristics, offshore wind power has significant seasonal differences and has adverse effects on peak regulation in regional and provincial grids for most of the year. Such adverse effects on peak regulation are more prominent in regional grids. For access to a wind farm, the surrounding grid planning and load development should be fully coordinated, the wind power delivery line and section capacity should be rationally arranged, and if necessary, a small amount of peak generation of offshore wind power may be abandoned to reduce investments in delivery lines.

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