For Wind Unstable Wind Power Volatility Modeling Method of Research

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Abstract — To model the fluctuation characteristics of wind power is the basis for solving wind power integration problems. Considering the correlation and smoothing effect of wind power, the paper studies statistical models of wind power fluctuations in different spatial and temporal scales. It first uses hypothesis testing to analyze the distribution model of wind power fluctuations based on measured data, verifying that the combined Gaussian distribution model has higher fitting precision than normal distribution. The paper then establishes the combined Gaussian distribution model and the confidence interval model for the probability density distribution of wind power variation pattern, and studies the law about the scale influence on parameters. Then the evaluation index of smoothing effect which can reflect the effect of wind-farm aggregation on smoothing wind power fluctuations is defined. And the relationship between such index and the correlation coefficient modeled as the linear function reflects the growth and decline relationship between smoothing effect and correlation. The paper proposes the statistical methods for evaluating large-scale wind power fluctuation and smoothing effect and correlation, which improves the accuracy of the fluctuation models and the integrity of indices.

Keywords - Wind power; Volatility; Characteristic analysis; Modeling

I. INTRODUCTION

Belongs to green energy, wind power has proven can take advantage of the wind energy resource is about 1 billion kW, at least the equivalent of more than 40 installed capacity of the three gorges power plant, by the end of 2005, the national total of built and put into operation of wind power equipment capacity is 105.59 kW, including a total of 40 installed capacity is more than 6000 kW of large wind farms parallel operation, has been parallel operation of wind power installed capacity is 1.0411 million kW, this is just the beginning of a wind power generation in China, in 2010, the wind power installed capacity has reached 5 million kW [1]. And wind resources distribution features and the layout to match the power load, the wind power development in China is given priority to with grid type, presents the typical cluster development, weak power grid access and long distance delivery. Volatility and randomness of wind power to the grid energy balance and voltage adjustment pressure, increase the difficulty of the power grid planning and scheduling, has become the bottleneck for the further development of wind power [2, 3]. To master the volatility of wind power in the inherent law of different time and space scales is the key to solve large-scale wind power grid operation problem. The wind resource distribution will lead to large scale wind power overall output volatility compared to scale up to the individual volatility has a weakening trend, a phenomenon known as the "smoothing effect" [4]; And geographically adjacent to the valley of the wind field (fan) output peak changes over time tend to be consistent with the phenomenon is called correlation. They are two aspects of large-scale wind wave characteristics of unity of opposites, the stronger the wind power output correlation, are complementary to each other, finally smooth effect is poorer, and smooth the better the results. Smoothness and correlation are two main expression of wind power fluctuation, which has now a lot of research attention. Temporal aspects, Shafiullah G M in the statistical analysis of the actual wind power output data, on the basis of qualitative description Inner Mongolia region in the form of chart in detail the change trend of different space-time scale wind wave characteristics [5]; Similarly, Hou T and He Z, respectively to the northeast, wind power output volatility in Gansu province and Jiangsu coastal wind power output characteristic has carried on the qualitative analysis and quantitative description [6,7]. In one of the few articles involves the modeling of the literature, some simple power curve model based on the measured wind data [8]. Some use the normal distribution model of wind power rate; there are based on the wind data of man-made structure, simple mathematical model is established [9,10]; wind field is established in the output correlation coefficient and wind field distance between the exponential models [11,12]. In frequency domain, the literature are established from the Angle of the power spectral density of the wind speed fluctuation characteristic of frequency domain model, a more accurate link will wind speed and wind power output; There are literature with the method of Fourier decomposition, fan output was analyzed the influence mechanism of the overall volatility. The remainder of this paper is organized as follows. Section 2 analyzed the effect factors of wind power fluctuation. Section 3 established a probability distribution model of wind power fluctuations, as well as, the section 4 put forward a confidence interval of high wind velocity model. Section 5 presented a theory of wind power smoothness and correlation. Conclusions are summarized in Section 6.
II. WIND POWER FLUCTUATION ANALYSIS

Due to the randomness active output of wind farms, wind farms and dispersivity of the distribution of wind turbines, it is necessary to study the correlation of regional wind power fluctuation problem, as shown in figure 1 and 2 for wind farms.

![Wind farm land](image1)

![The sea wind](image2)

A. Seasonal Power Fluctuations and Days Power Fluctuation Characteristics of Wind Power

Wind is caused by the pressure difference on the surface of the earth, and the pressure difference is caused by solar radiation caused by uneven heating on the ground, so the original source of wind energy is the sun. Seasonal variation and alternation of day and night are associated with the fluctuation of solar radiation. Because the solar radiation has different seasonal cycle and intraday cycle, it is necessary to investigate the wind wave characteristics corresponding mode.

Before the analysis of wind power fluctuation characteristics, first of all, the network wind power development in do the introduction. By the end of 2005, the national total of built and put into operation of wind power equipment capacity is 105.59 kW, including a total of 40 installed capacity is more than 6000 kW of large wind farms parallel operation, has been parallel operation of wind power installed capacity of 1.0411 million kW, this is just the beginning of wind power generation in China, in 2010, the wind power installed capacity has reached 5 million kW, figure 3, respectively, for the development trend of wind power installed capacity in China.

![Total installed capacity of wind power in China](image3)

Figure 3. Total installed capacity of wind power in China

Figure 4 shows the total output of wind power in China in 1 year 12 months of volatility, maximum power is 1571.37 MW in December, and the minimum power is August 421.08 MW, seasonal peak valley difference of 115029 MW, is 73.47% of the peak power. In general, wind power is big in winter, summer minimum output, this summer and the winter wind speed, wind speed also small.

![Wind power curve](image4)

![Average coefficient of variation of wind power fluctuations](image5)

B. Days of Wind Power Fluctuation Characteristics of Seasonal Differences

To investigate the change of seasons in a day of fluctuating wind model, calculate the average capacity factor of every year of the standard deviation, and standardized coefficient of variation. Is also called the standard rate, variation coefficient is the ratio of standard deviation and average, measured data of each observed value variation degree in statistics. Using variation coefficient can eliminate units or the average of two or more different materials the influence of the variation is. As shown in figure 5.

Can be seen from the diagram, each region at 6:30 to 12:30 variation coefficient, the biggest show in this time period, a year of wind power fluctuation rule difference is very big. And low coefficient of variation before and after
the midnight that the wind power, change rule is relatively fixed in a year.

C. Wind Power of Regional Correlation

Through the analysis can be found, installed wind regions had obvious regional correlation of wind power fluctuations, in order to confirm the correlation, calculate each power fluctuations of correlation coefficient between two wind power base, the correlation coefficient is a variable related degree between indexes. In \( r \) sample correlation coefficient, correlation coefficient value in the range of \([-1, 1]\). The \( |r| \) value, the greater the degree of linear correlation between variables is higher; \( |r| \) value, the closer the 0, the lower the degree of linear correlation between variables. Wind farm in someone province as an example, the annual average wind power fluctuations between base correlation coefficient is given in figure 6.

![Figure 6. Correlation coefficient between wind farms](image)

Can be seen from the diagram above, in Dongying, Yantai, Qingdao, Linyi, between the four areas of wind power fluctuations in the average correlation coefficient is more than 0.9, explain the four areas of regional correlation is very strong, and is a positive correlation.

III. PROBABILITY DISTRIBUTION MODEL OF WIND POWER FLUCTUATIONS

A. Wind Power Probability Distribution Model of Rapid Fluctuations

Wind power variation probability distribution model is the basis of quantitative analysis of wind power smoothness and correlation. Define wind power output rate \( P_t \):

\[
P_r = \frac{P(t+1) - P(t)}{P_S}
\]

(1)

Among them: \( P(t) \) is wind power total output when it is \( t \); \( P_S \) is the total installed capacity.

This paper introduced Gaussian mixture model to improve the fitting precision of the probability distribution, the probability density function of the Gaussian mixture model is several weighted Gaussian probability density function. In this paper, the one dimension of the Gaussian mixture model is shown in type (2), (3).

\[
f(x) = \sum_{j=1}^{K} \alpha_j N\left(\mu_j, \sigma_j^2\right)
\]

(2)

\[
N\left(\mu, \sigma^2\right) = \frac{1}{(2\pi\sigma)^{1/2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}
\]

(3)

In particular, a component of the mixed Gaussian model \( f(x) = N\left(\mu, \sigma^2\right) \) is the one dimension probability density function of normal distribution. In this paper, by using maximum likelihood estimation algorithm, maximum likelihood function improvement for maximum likelihood function expected, on the premise of guarantee the estimation precision was greatly improve the reliability of the algorithm.

Fitting function is shown in the type (4), \( \alpha_j \) is each component weight.

\[
f(x) = \alpha_1 \times \frac{1}{\sqrt{2\pi\sigma_1}} \exp\left(-\frac{x^2}{2\sigma_1}\right)
\]

\[
+ \alpha_2 \times \frac{1}{\sqrt{2\pi\sigma_2}} \exp\left(-\frac{x^2}{2\sigma_2}\right)
\]

(4)

With different number of fan using the above model, can get better fitting effect, the fitting parameters as shown in table 1.

> Table I Fitting parameters of Gaussian mixture model

<table>
<thead>
<tr>
<th>The number of fan</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_1 )</td>
<td>0.0027</td>
<td>0.0020</td>
<td>0.0016</td>
<td>0.0014</td>
<td>0.0012</td>
</tr>
<tr>
<td>( \sigma_2 )</td>
<td>0.0085</td>
<td>0.0058</td>
<td>0.0045</td>
<td>0.0038</td>
<td>0.0033</td>
</tr>
<tr>
<td>( \sigma_3 )</td>
<td>0.6525</td>
<td>0.6352</td>
<td>0.5842</td>
<td>0.5667</td>
<td>0.5498</td>
</tr>
<tr>
<td>( \sigma_4 )</td>
<td>0.8475</td>
<td>0.8648</td>
<td>0.4158</td>
<td>0.4330</td>
<td>0.4502</td>
</tr>
</tbody>
</table>

Generally, the fan output second level rapid fluctuations are rooted in the local turbulence of air mass. Turbulent air mass with high randomness can assume \( P(t+1) \) and \( P(t) \) are independent of each other. Second level power fluctuations are the smallest units of wind power fluctuations, therefore, the probability distribution model is established to fundamentally grasp the inherent law of wind power fluctuations, accordingly can also be deduced for a longer time scale characteristics of wind power fluctuations.

B. Scale Wind Power Output Volatility Modeling Analysis

Large-scale cluster interconnection is the main development of wind power in China. Large wind power clustered on geographic scale across 100 ~ 500 km, completed by regional grids secondary FM active balancing...
tasks. Here choose network multiple wind fields in north China province 5 min interval of wind power output data to calculate. Established by fitting, can prove that above also apply to the Gaussian mixture model on the analysis of the cluster minutes level output fluctuations, but the scale is different, the specific model parameters have certain differences.

Respectively using normal distribution model and the two-component Gaussian mixture model of single or multiple wind field of the total output power rate probability distribution fitting, the fitting error as shown in table 2 and table 3.

In the table 2 and table 3: by using the Gaussian mixture model fitting error is much less than normal distribution fitting error. On the other hand, for the same time scale, the same with normal distribution, multiple wind field the fitting error of the total output is lower than a single output deviation, fitting multiple wind field output rate always probability distribution is more close to the normal distribution.

| Table II Fitting Deviation of Single-Farm Output Volatility Probability Distribution |
|---------------------------------|-----|-----|-----|
| A single output of wind field   |     |     |     |
| 5min                            | 34.35 | 31.51 | 31.98 |
| Normal fitting deviation%       |     |     |     |
| 10min                           | 8.82  | 9.85  | 12.69 |
| Gaussian mixture distribution fitting% |     |     |     |
| 15min                           |     |     |     |

| Table III Fitting Deviation of Multi-Farm Output Volatility Probability Distribution |
|---------------------------------|-----|-----|-----|
| Cluster wind field              |     |     |     |
| 5min                            | 22.06 | 24.42 | 25.91 |
| Normal fitting deviation%       |     |     |     |
| 10min                           | 4.68  | 5.44  | 8.25  |
| Gaussian mixture distribution fitting% |     |     |     |
| 15min                           |     |     |     |

Obviously, when the two-component one-dimensional two weight variance gradually close to the Gaussian mixture model, the weight of one component or when tends to zero, a one-dimensional two-component mixed Gaussian model will degenerate into a normal distribution.

To sum up, the wind scale is small, need to adopt a one-dimensional two-component Gaussian mixture model for the variation of the wind power, the probability distribution of a more accurate description, but with the increase of scale of wind power, the probability distribution gradually close to the normal distribution.

IV. THE CONFIDENCE INTERVAL OF HIGH WIND VELOCITY MODEL

A. Fluctuations Confidence Interval Between R and the Number of Fan Power Function Model

Two-component one-dimensional although the Gaussian mixture model can more accurately depict the probability density distribution of wind power volatility, but not directly given wind volatility increased as the number of crew change rule. Here introduced fluctuation confidence interval R.

\[ P(X < R) = P \]

(5)

Among them: \( P \) is probability, \( X \) is the absolute value of wind power fluctuation rate; \( P \) value for a given probability, \( P \) is the specific values can be determined according to the demand, in this article studies the value is 0.9. Fitting function is shown in type (6).

\[ P(n) = 0.01717 \times n^{0.4492} \]

(6)

Analysis type (6), we can see that with the increase of , present attenuation characteristics of power function value. To the wind farm or different wind conditions of different location, fluctuation believe cumulative value With the increase of the number of fan, the power function coefficient vary slightly, but the power function relationship remain unchanged.

B. Wind Speed Factor Analysis

In order to analysis the influence law of wind speed and fan control strategy of the model, in one day’s data, for example, taking wind speed at 3~6 m/s , 8~10 m/s and greater than 13 m/s interval, the change rate of the change of wind speed and power draw the corresponding probability distribution image respectively as shown in figure 7 in implementing line, dotted line and point line.

![Figure 7. Different wind speed fluctuations](image)

First of all, seen from the figure 7(a), with the increase of wind speed, wind speed its volatility; In addition, comparison of figure 7(a) in a solid line and dotted line to see, when the wind speed is lower than the rated wind speed, with the increase of wind speed, wind speed fluctuations intensifies directly led to the fan power output increased; From figure 7(a) and (b) the dotted line and point in the line,
the wind speed is higher than the rated wind speed, while its volatility, but fan output power fluctuation is weakened to a certain extent, this is due to the speed and paddle type fan after winds reach above rated wind speed by adjusting the pitch Angle and speed to control the output power fan near the rating, make sharp fluctuations in wind speed cannot be on the fan output power fluctuation is proportional to the ground.

V. WIND SMOOTHNESS AND CORRELATION ANALYSIS

In order to measure the smoothing effect of wind power, define smooth coefficient index $S$, definition to comprehensively consider the fluctuation of the whole and local characteristics.

Definition 1: use a standardized sequence of wind power output of individual standard deviations compared with the overall standard deviation of relative changes value measure, as shown in type (7).

$$S_1 = \sigma_r - \sigma_s$$  \hspace{1cm} (7)

For single standard values of $\sigma_r, \sigma_s$ values for the cluster

Simple and intuitive, easy to understand, that definition applies to the fixed time scales, comparing the smoothing effect of different spatial scales, but not suitable for evaluation in fixed space scales, the smoothing effects under different time scales. Math can prove that, for the wind power output sequence is obtained by calculating mean to different time scales. Mathematically, for the wind power output sequence, the smoothing effect of different scale has good consistency. Smoothing coefficient is smaller, which indicates that the cluster output fluctuations relatively single field effect is poorer, the improvement in namely the smooth effect. Use in north China in a wind belt with a 7, adjacent to the wind field data under different time scales using two methods of definition $S$. The results as shown in table 5. With the increase of time scales, near the correlation between wind field output enhancement, makes the smoothing of the efforts of the cluster effect is abate, smoothing coefficient $S_1$ decreases.

<table>
<thead>
<tr>
<th>Time scale</th>
<th>5min</th>
<th>10min</th>
<th>10min</th>
<th>1hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$</td>
<td>0.2427</td>
<td>0.2576</td>
<td>0.2576</td>
<td>0.3467</td>
</tr>
</tbody>
</table>

Based on a certain wind cluster data in north China, wind field was calculated by the type (9) correlation coefficient between the two, one, two wind field of the output sequence is seen as a random variable $X, Y$.

$$r_{xy} = \frac{1}{n} \sum (x_i - \mu_x)(y_i - \mu_y)$$  \hspace{1cm} (9)

Use of experience, with the increase of correlation coefficient, show the approximate linear smoothing coefficient decreases, using linear function fitting, get the fitting function:

$$S = -0.2872 \times r_{xy} + 0.2775$$  \hspace{1cm} (10)

Correlation coefficient of the minus sign before the smoothing effect and negatively correlated with correlation; In addition, seen from the type, when the smoothing coefficient is 0, the corresponding correlation coefficient is about 1, namely the two wind field output is completely related, this is consistent with experience.

VI. CONCLUSION

This study based on wind field measured data, using mathematical methods, statistical analysis and research the different time and space scales of the efforts of the wind wave characteristics. Research process followed from a single field, short time scales to the cluster, and longtime scales of research ideas, get the following conclusion: The results showed that a one-dimensional two-component mixed Gaussian distribution model can greatly improve the fitting precision of the model. But with the increasing scale of wind power cluster, one of the components of mixed Gaussian distribution or two weight variance convergence, gradually close to the ordinary normal distribution model. So when the accuracy is not high, large scale wind power output volatility cluster distribution normal distribution approximation are still available.

The paper defines the cumulative probability under the given power rate $c_i R_c$ can be used to measure different space-time change rule of the efforts of the wind fluctuations. With the increase of number of fan, the indicators present power function decline, but the concrete numerical value by the wind speed, the types of fan, fan control strategy factors such as joint decision. Paper introduces smoothing coefficient index, able to compare different space-time scale wind volatility consistent smooth effect, fill the gaps in the existing study such indicators.Paper discusses the model of wind power between smoothness and correlation relationship, smoothing coefficient is established and the related coefficient is a function of the mathematical model, the model can quantitatively describe the mathematical relationship between the smoothing effect and the correlation, make this kind of description model of wind power output characteristics of a more complete.

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REFERENCES


