The Estimation of Wind Power Station on the Basis of Fuzzy Regression Model to Forecast the Speed and Direction of the Wind

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ABSTRACT

To forecast the wind speed and the angle of its direction, it is suggested to use autoregression based on the concept of fuzzy system, which is recognized as a fairly convenient modeling tool. The main goal of fuzzy regression analysis is to find a regression model that satisfies all the observed fuzzy data within specified optimality criterion. According to this method, the regression coefficient is fuzzy numbers, which can’t be expressed as a number of the interval with membership values. In this work, the wind speed and direction are predicted for the Far Eastern coast. It is shown that on this basis the power and generation of a wind power plant with the possibility of covering its load schedule, and the function of energy storage can be determined. High introduction of wind power plants into system leads to some inconveniences in the operation of operator systems, primarily due to unpredictable and volatile nature of wind speed, and wind power generated, respectively. Despite fact that the power generated at the wind form is not regulated by the system operator, accurate prediction of wind speed and the angle of its direction could solve this problem, thereby making a significant contribution to improving the reliability of power supply systems.

INTRODUCTION

Rising fossil fuel prices accelerate the transition to renewable energy. Among the diversity of such sources, at present time, wind energy as one of the most
effective and clean energy sources is in rather great demand. From 1999 to 2017, the total installed capacity of wind turbines (wind turbines) in the world increased from 14 to 540 GW, with an increase in recent years of over 10% per year. The wind power engineering has received the greatest development in China, USA, Germany, Spain, India, and United Kingdom. In individual countries and regions, the share of installed capacity of wind turbines exceeds 20% and even 40% (Denmark). The maximum unit capacity of operating wind turbines is 8 MW, in the process of developing wind turbines with a capacity of up to 12 MW. Based on the level and rate of development of global wind energy achieved in 2017, it is assumed that by 2030 the installed capacity of wind turbines reaches 977 MW.

However, the integration of such energy sources into the electric power system causes various kinds of problems that today find their solution [1]. Along with this, it should be noted that the power generated by wind power plants strongly depends on meteorological factors, in particular, wind speed [2]. Accordingly, an unexpected change in WPP power may lead to such production costs as the need to increase the main backup power and increase the risks in the reliability of power supply [3].

System operators need to predict changes in power generated by wind power plants and to know exactly the volume of generation in order to plan the necessary amount of reserve and manage the processes in the network, taking into account the forecast data. To reduce the volume of reserve power and increase the level of WPP penetration into the power grid, accurate prediction of wind speed is necessary [4].

FUZZY LOGIC REGRESSION MODEL

Due to the complexity of building a wind speeds model, as well as the influence of unrecorded meteorological factors, such as air temperature, pressure, humidity and others, it is not always possible to unambiguously determine the type of statistically stable dependence \( y = f(x) \). In this case, you can try to get a single adequate model on the original sample, making it much more complicated. Another way may be to build a piecewise regression. The disadvantage of the first (re-complicated) model is a significant risk of its use for prediction. Piece models require a fairly accurate definition of the definition of its individual parts. An alternative option is to build a model in the form of a system of vague rules. The advantage of such models is that the resulting solution is a fairly smooth function. The boundaries of the individual parts of the model are blurred, which reduces the requirements for their precise definition. The accuracy of the approximation can be varied by increasing or decreasing the number of blurry rules used. Fuzzy MISO type models (multiple input, single output) are a set of rules of the form [5]:

\[
IF \quad x_1 \in A_{i1} \quad \& \quad \ldots \quad \& \quad x_n \in A_{in} \quad THEN \quad y = \eta^f(x), \quad i = 1, \ldots, m, \quad j = 1, \ldots, n
\]
where $A_i$ – fuzzy subset for variable $x_j$ with accessory function $\mu_{A_i}(x_j)$; $m$ – the number of rules, $n$ – number of factors, $\eta'(x_j)$ – functions, determining the local dependence of the response on the regression set $x = (x_1, \ldots, x_n)^T$.

Clear variable value $y$, obtained using the defuzzification method of the center of gravity, is calculated by the formula:

$$y = \frac{\sum_{i=1}^{m} \mu_i \eta_i}{\sum_{i=1}^{m} \mu_i}; \quad \mu_i = \prod_{j=1}^{n} \mu_{A_i}(x_j)$$

(2)

The model in the form (1), (2) will be called the FLR (Fuzzy Logic Regression) regression model. Consider the FLR regression construction technique for the case of one-dimensional dependence construction.

With one variable, the rule system (1) takes the form:

$$IF \ x \in A_i \ THEN \ y = \eta_i'(x_j), i = \overline{m}, j = \overline{n}$$

(3)

where $A_i$ have a membership function $\mu_{A_i}(x)$.

The following are used as repressors:

$$\mu_{A_1}(x), \ldots, \mu_{A_m}(x), x\mu_{A_1}(x), \ldots, x\mu_{A_m}(x)$$

(4)

**FUZZY WIND MODEL**

It is known that wind speed can be represented by the Beaufort scale [6]. In it, wind speeds are divided into 9 intervals, among which intervals for the weakest and strongest winds can be eliminated, since at the minimum wind speed there is not enough impact on the wind power installation, and at the strongest installation they are turned off to avoid destruction. The Beaufort scale must be described by the membership functions of linguistic variables, that is, it must be indicated which wind speed $u$ relates to which degree of belonging to which linguistic variable. In this case, the so-called LR-functions [7] are used, which can be easily represented graphically. Example, a wind speed of 11 m / s can be equally attributed to both fresh wind and strong wind, a wind speed of 18 m / s most likely refers to very strong wind, but to some extent can be attributed to strong.
Along with this, the authors considered the prediction of the wind direction and proposed membership functions for individual wind directions. The basic directions of the world are taken as the basic directions: East - zero reading from the positive direction of the abscissa wasp; North is the positive direction of the ordinate wasp, shifted by 90 degrees counterclockwise; West - the negative direction of the abscissa of the wasp shifted by 180 degrees counterclockwise; South - negative direction of ordinate wasp shifted by 180 degrees counterclockwise (Figure 1).

Such a set of membership functions is approximate, therefore intermediate membership functions are introduced: the Northeast, the Northwest, the Southeast and the Southwest. However, to control wind turbines based on fuzzy logic and this gradation of the membership function may not be enough. In this regard, the authors propose new gradations of wind direction, namely: East-North-East (ENE), North-North-East (NNE), North-North-West (NNW), West-North-West (WNW), West-South-West (WSW), South-South-West (SSW), South-South-East (SSE) and East-South-East (ESE).

CONVERSION OF PREDICTED WIND SPEED TO POWER

It is known that the power at the output of wind turbines is directly dependent on the speed of the wind flow, which varies greatly in time, on local weather and the surface of the area. The relationship between the wind speed passing through the swept area of installation $A$ (m$^2$) and power is expressed through the formula.
\[ P = C_p \cdot \rho \cdot A \cdot \frac{V^3}{2} \]  

(5)

where \( \rho \) – is the airflow density (kg / m\(^3\)) depending on the temperature and air pressure, \( A \) is the area swept by the blades, \( V \) is the wind speed, \( C_p \) – efficiency ratio of wind turbines, \( \lambda \) – coefficient of speed.

One of the simplest ways to convert wind speed into power is to use the power characteristic from the manufacturer of a particular installation. A similar method and the results of the study are described in detail in [8–10].

**FORECAST RESULTS**

For the day-ahead forecasting, it is necessary to obtain a separate forecast for each of the time series coefficients: wind speed and direction. The obtained results of wind speed prediction are presented in Table I, while the probabilistic characteristics of the wind flow are determined: mathematical expectation (\( m_\lambda \)), standard deviation (\( \sigma_\lambda \)) and variance (\( D_\lambda \)). On this basis, using the formula (5), we determined the electric power of a wind turbine (\( P \)).

**TABLE I. GENERATION OF ACTIVE POWER OF WIND TURBINES WITH ACTUAL AND PREDICTED WIND SPEED VALUES.**

<table>
<thead>
<tr>
<th>Times of day</th>
<th>( m_\lambda )</th>
<th>( \sigma_\lambda )</th>
<th>( D_\lambda )</th>
<th>( \sigma_\lambda )</th>
<th>( P ), MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>14</td>
<td>12,2</td>
<td>12,9</td>
<td>13,68</td>
<td>7,88</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>13,1</td>
<td>31,0</td>
<td>11,47</td>
<td>12,32</td>
</tr>
<tr>
<td>6</td>
<td>11</td>
<td>13,4</td>
<td>21,8</td>
<td>7,69</td>
<td>11,11</td>
</tr>
<tr>
<td>9</td>
<td>11</td>
<td>12,6</td>
<td>14,5</td>
<td>11,12</td>
<td>13,73</td>
</tr>
<tr>
<td>12</td>
<td>15</td>
<td>11,9</td>
<td>20,7</td>
<td>31,00</td>
<td>12,51</td>
</tr>
<tr>
<td>15</td>
<td>13</td>
<td>10,3</td>
<td>20,8</td>
<td>17,49</td>
<td>11,18</td>
</tr>
<tr>
<td>18</td>
<td>15</td>
<td>14,7</td>
<td>2,0</td>
<td>28,71</td>
<td>26,24</td>
</tr>
<tr>
<td>21</td>
<td>14</td>
<td>10,7</td>
<td>23,6</td>
<td>17,49</td>
<td>8,65</td>
</tr>
<tr>
<td>24</td>
<td>14</td>
<td>12,2</td>
<td>12,9</td>
<td>13,68</td>
<td>7,88</td>
</tr>
</tbody>
</table>

**TABLE II. ANGLE FORECAST WIND DIRECTION.**

<table>
<thead>
<tr>
<th>Times of day</th>
<th>0</th>
<th>3</th>
<th>6</th>
<th>9</th>
<th>12</th>
<th>15</th>
<th>18</th>
<th>21</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual value</td>
<td>112,5</td>
<td>112,5</td>
<td>112,5</td>
<td>112,5</td>
<td>112,5</td>
<td>90</td>
<td>90</td>
<td>157,5</td>
<td>112,5</td>
</tr>
<tr>
<td>Forecast value</td>
<td>96</td>
<td>102</td>
<td>89</td>
<td>78</td>
<td>215</td>
<td>127</td>
<td>106</td>
<td>158</td>
<td>96</td>
</tr>
<tr>
<td>Error</td>
<td>14,6</td>
<td>9,3</td>
<td>20,8</td>
<td>30,6</td>
<td>47</td>
<td>41</td>
<td>17,7</td>
<td>3</td>
<td>14,6</td>
</tr>
</tbody>
</table>
From table I it follows that the error in predicting the mathematical expectation of wind speed for three hours in a period is from 2 to 31%.

Along with this, the forecast of the direction of the wind, measured in the corners (Table II). The counting of the angle begins with the country east from the positive direction of the abscissa of wasp.

From table 2 it follows that the error in predicting angle of wind direction for three hours in the period ranges from 3 to 47%.

Thus, the initial information for controlling wind turbines can be used: expectation ($m_x$) and standard deviation ($\sigma_x$) of wind speed, as well as wind direction, which determines the turning angle of the gondola. This allows you to go to the predictor control of the wind energy installation according to the rules, taking into account the membership functions.

CONCLUSIONS

1. Calculations show that predicting wind speed and its angle based on fuzzy regression can be performed with acceptable accuracy three hours ahead. This allows you to plan the production of electricity using wind turbines.

2. For the first time, wind speed forecast is supplemented with wind direction predicting. This allows, at the second stage of power generation of the wind turbine, to carry out the predictor control of the nacelle, while the attack coal of the blade can be a secondary control element of the wind turbine.

3. In general, wind turbines should be controlled on the basis of fuzzy rules with choice of their priority impact, which allows for the highest energy efficiency of both individual plants and whole wind power plant.

REFERENCES


