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Short-term Wind Speed Prediction Based on Grey System Theory Model in the Region of China

***Abstract**.Short-term wind speed forecasting is useful for power system to regulate power dispatching plan, decrease reserve power needed and increase the reliability of system. The method of the short-term wind speed prediction is proposed in this paper. The data of wind speed in Dafeng, Jiangsu Province of China is predicted by the model combined with the grey system theory (GST). A grey system model consists of accumulating generation operation of original wind speed sequence data, data processing and wind speed forecasting. The hourly mean wind speed data at 85 meters above ground level of one year is generated by meteorological tower operated by the local bureau of meteorology. In this paper, the hourly average wind speed measured every an hour of 24 hours on Jan.1st, 2008 are the initial dataset for predicting. The result of wind speed is predicted by the grey system theory model with 0.14% of minimum relative percentage error (MRPE) and 7.22% of maximum mean absolute percentage error. The wind speed predicted values are given by the graphs and tables, which can be used easily for assessment of short-term wind energy in the different regions within China.*

***Streszczenie.** W artykule zaproponowano metodę krótkookresowego prognozowania szybkości wiatru. Do prognozowania zastosowano teorię GST (Grey system theory). System składa się z panelu zbierania i przechowywania danych, przetwarzania danych i prognozowania. Zbierane są dane prędkości wiatru 85 metrów nad powierzchnią ziemi. (**Krótkookresowe prognozowania szybkości wiatru bazujące na modelu Grey System Theory**)*

Keywords: Wind energy resource, Grey system model prediction, Wind energy density.
Słowa kluczowe: szybkość wiatru, prognozowanie

Introduction

There are a lot of large wind farms connected with the grids in China. Because wind power is determined by wind speed and the wind speed has the nature of randomness, the power quality and the operation of power system can be badly influenced when the wind power penetration limit is exceeded. Therefore, wind speed forecasting is very important to the operations of wind power plants and power systems. It can relieve or avoid the negative influences of wind power plants on the power systems and enhance the competitive ability of wind power plants in the electricity markets. Additionally, the wind speed forecasting is classified into two types: mid-and-long term wind speed forecasting and short-term wind speed forecasting. The mid-and-long term wind speed forecasting is an important basic work of wind farm layout and design, however, the short-term wind speed forecasting is useful for power system to regulate power dispatching plan, decrease reserve power needed and increase the reliability of system[1-2]. Nowadays, wind speed forecasting is a wind power research hotspot, and the most urgent need is to improve the short-term wind speed forecasting method. Therefore, this paper aims to provide a short-term wind speed prediction method so that it could be applied to the wind power forecasting for the hybrid wind/coal generation of the grid connected with wind farms.

Today, there are four kinds of methods for wind speed assessment [3-4]. Assessment based on historical observation data of meteorological administration. Assessment based on the meteorological tower observations. Numerical simulation method of wind speed. Satellite remote sensing technology applied to the wind speed assessment. However, there are two problems for the first and second methods which are based on the data from meteorological observations [2, 5]. Firstly, the wind speed from meteorological observation is measured at the height of 10 meters above ground. And nowadays, a lot of hubs of wind turbines are higher than 70 meters. However, wind speed depends on the local terrain, surface conditions and atmospheric stability, so it is difficult to extrapolate the wind speed at the height of wind turbine hub based on the data observed at 10 meters above ground. Secondly, because the distribution of meteorological stations in China is not well balanced, the results of the wind speed assessment may not be accurate. And the numerical simulation used in the wind resource assessment is an effective way. In general, it is feasible to assess wind speed applying numerical simulating technique. In theory, numerical simulating technique based on the mathematical and physical description of dynamic and thermodynamic movement in atmospheric boundary layer get the advantage over the spatial interpolation which just depend on the data from meteorological observations. But there is also the disadvantage in this approach, which needs large amount of data calculation. The satellite data for wind resource assessment also has some limitations that the information of the time and spatial resolution is too low and the assessment accuracy is also poor. So there are some weaknesses about methods discussed above, and these methods are all based on a long time such as a month or a year. There are very few assessment methods regarding the short-time wind speed forecast. The mid-and-long term collection and processing of wind speed data is important to guide the production and daily lives of people, and help the assessment, layout and design of wind farms, however, the short-term wind speed forcasting is studied for the requirement of the joint dispatching of electric power in the wind farm. They are all play important, indispensable and useful roles in the wind power research, but the most emergent need is to develop the short-term wind speed prediction. So in this paper, the key to the study is short-time wind speed prediction.

This paper proposes a new method of short time (hourly-level) wind speed prediction based on the grey system prediction models GM (1, 1) to relieve operation and dispatching pressure due to a large scale of wind power grid integration. During the last three decades, the grey system theory has been developed rapidly. It has been applied widely and successfully in various systems, such as social system, economic system, etc [6]. But it isn't reported that the gray theory is used in the field of the wind speed assessment. Grey system prediction is based on statistical method, which is similar to time-series method. Box-Jenkins has made great contributions in time-series method, and if just the time series of the wind speed or power is known, prediction model could be established by this method [7,8]. Furthermore, for time-series method, ARIMA (Autoregressive Integrated Moving Average) model is most widely used [9]. ARIMA is suite for super-short-time (0～3 h) wind speed prediction, and based on the time series data measured, the prediction models could be established by curve fitting and parameter estimation. Although it has good prediction effect, there are some weaknesses which are (1) the requirement of a large number of data samples, (2) the requirement of good distributing rules and determinate development tendency of data samples, (3) the huge calculation, and (4) the discrepancy between calculation and analysis results. However, according to grey system theory, a new analysis method is proposed, which is the grey correlative degree analysis method. And the method measures the correlative degree by the geometric similarity or dissimilarity of the development tendency of factors. Because the grey correlative degree analysis method is based on the development tendency of factors, there are not the weaknesses of ARIMA mentioned above. The strengths of grey system are as follows: it is not necessary to know the working principle, structure and physical model of the system predicted, and taking the wind power for example, it is difficult to establish its accurate physical model. Besides that, the number of samples could be small, and the good distribution and development trend of samples are also not needed [10]. Compared with the other prediction methods, the feature of the grey forecasting model is that: the smaller dispersion degree or grey degree of data is, the more accurate prediction is. Additionally, although the grey forecasting model is suit for the data with any time scale, its predictive value is just the trend value when the time scale of data becomes long, which is introduced detailedly in the paper [11]. That could be say, as time goes on, more and more disturbance factors would go into the system, which causes that the longer time span is, the bigger grey degree is and the less practical significance of predictive value is[11]. As a result, it is the most appropriate to apply the grey forecasting model GM (1, 1) to the short-term wind speed forecasting.

A brief description of the grey system theory model used in the short time prediction on some region of China is presented in Section 2, and some details of the theory used to calculate wind speed and result analysis are in Section 3. Conclusions follow in section 4.

Grey System Theory in General and GM (1, 1) Model

According to modern control theory, there are three dynamic systems classified by using information adequacy criterion, which are black system, grey system and white system. The information of black system is complete unknown, while the information of white system is complete clear. Between these two systems, gray system's critical characteristic is information incompleteness. In realistic life, the problems with uncertainties and less statistic data belong to the field of gray system. Therefore, in accordance with the feature of information incompleteness, grey system theory develops and extracts the valuable information from the known information to describe and monitor the operation behavior and evolution law of system effectively. Furthermore, there is no special restriction for observation data and its distribution. Grey system theory is established by the scholar Julong Deng in 1982 to solve these problems with small size data samples. During the last two decades, the grey system theory has been developed rapidly and catches the attentions of many researchers [12-13].

The grey model GM (1.1) is the main model of grey system prediction theory, as a single input and single output system. This model is a time series forecasting model, which is created with a small amount of data (four or more) and still can provide fine forecasting result. An important difference between the grey forecasting model GM (1, 1) and other statistical forecasting models is the accumulating generation. The model has time-varying coefficients. The original time data sequence $X^{(0)}$ assumed is described as follows [14-15]:

(1) $$X^{(0)} = \{x^{(0)}(1), x^{(0)}(2), ..., x^{(0)}(n)\} \qquad n \geq 4$$

where，n is the number of raw sequence data. In order to build GM (1, 1) model, it is required that $x^{(0)}(k) \geq 0$, k = 1, 2, ……, n. But for the actual dynamic system, its sampled values $x^{(0)}(k)$ are not always non-negative, In order to obtain the data from the random rules, the sequence needs to be processed by the accumulating generation operation (AGO). By accumulation generation operator (AGO), the integral characteristic contained in the raw data could be uncovered completely. And when the nonnegative smooth sequence is processed by AGO, the law of approximate exponential growth can be presented. Furthermore, the smoother the sequence is, the more evident the exponential growth law is.

The cumulative sequences are generated from the original sequences $X^{(0)}(k)$ as follows:

(2) $$X^{(1)} = \{x^{(1)}(1), x^{(1)}(2), ..., x^{(1)}(n)\} \qquad n \geq 4$$

where

(3) $$X^{(1)}(k) = \sum_{i=1}^{k} x^{(0)}(i), \qquad k = 1,2,3...,n. \qquad n \geq 4$$

The first element of the original data sequence remains unchanged to serve as the first one of the new data sequence, the sum of the first and the second element of the original data sequence is served as the second one of the new data sequence, and the sum of the first, the second and the third element of the original data sequence is served as the third one of the new data sequence.

When the historical data is insufficient and scarce, the average generation is often used to complete the sequence with blanks in the prediction model. For equal time interval sequence, average generation is used to generate the new data from the average of two adjacent data.

The mean sequence $Z^{(1)}$ generated by $X^{(1)}$ is defined as:

(4) $$Z^{(1)} = \{z^{(1)}(1), z^{(1)}(2), z^{(1)}(3), ..., z^{(1)}(n)\}$$

where $z^{(1)}(k)$ is the mean value of the adjacent data of $X^{(1)}(k)$, i.e. The k starts from 2.

(5) $$z^{(1)}(k) = \frac{1}{2}(x^{(1)}(k) + x^{(1)}(k-1)), k = 2,3,...,n$$

Because the average generation is the equal-weight generation of the information before and after the blank, it also can be called the equal-weight generation of two adjacent data.

It was created with the original data sequence X (0) in other forecasting models, but in grey model it was created with the one-step accumulating generation sequence $X^{(1)}$ .Through accumulating the original data sequence, the randomness trend of the original data is reduced and we can get better simulative result.

Many researchers are interested in differential equations and they argue that differential equations are powerful tools in modern science because they can reveal the evolving dynamics of real world events deeply. However, the limitation of a differential equation is that it can only be used to describe continuous differentiable objects. Researchers often feel helpless when they face a discrete data sequence. But fortunately, grey system theory defines grey differential equations of sequence through profound analysis of differential equations, which is helpful when facing a discrete data sequence. Additionally, the core of grey system prediction theory is a grey model composed of a variety of grey differential equations. The least square estimate sequence of the grey difference equation of GM (1, 1) is defined as follows:

(6) $$x^{(0)}(k)+az^{(1)}(k)=u$$

Therefore, the whitening equation (10) is as follows:

(7) $$\frac{dx^{(1)}(t)}{dt}+ax^{(1)}(t)=u$$

$\frac{dx}{dt}$ is called a derivative of x, $x^{(1)}(t)$ is called the background value of $\frac{dx^{(1)}(t)}{dt}$, and "a" and "u" are parameters. Eq. (7) is called the basic form of model GM (1, 1). In the model, the parameters "a" and "u" are unknown, which can be obtained from the original sequence $X^{(0)}(k)$ and accumulated sequence $z^{(1)}(k)$. With more than two equations and two unknown parameters "a" and "u", it needs to use the least square method to find the optimal solution.

(8) $$[a,u]^T=\left(B^TB\right)^{-1}B^TY_n$$

where

(9) $$B=\begin{bmatrix}-z^{(1)}(2) & 1\\ -z^{(1)}(3) & 1\\ -z^{(1)}(4) & 1\\ \vdots & \vdots\\ -z^{(1)}(n) & 1\end{bmatrix}$$

(10) $$Y_n=\left[x^{(0)}(2),x^{(0)}(3),x^{(0)}(4)\cdots x^{(0)}(n)\right]^T$$

The "a" and "u" obtained are substituted into Eq.(10) and the solution of $x^{(1)}(t)$ at the time point k:

(11) $$\hat{x}^{(1)}(k+1)=\left[x^{(1)}(1)-\frac{u}{a}\right]e^{-ak}+\frac{u}{a}\qquad(k=0,1,2\cdots)$$

Because of $x^{(1)}(1)=x^{(0)}(1)$, the above equation can be expressed as:

(12) $$\hat{x}^{(1)}(k+1)=\left[x^{(0)}(1)-\frac{u}{a}\right]e^{-ak}+\frac{u}{a}\qquad(k=0,1,2\cdots)$$

To obtain the predicted value of the primitive data at the time (k + 1), the Inverse Accumulating Generation Operation (IAGO) is used to establish the following grey model.

(13) $$\hat{x}^{(0)}(k+1)=\hat{x}^{(1)}(k+1)-\hat{x}^{(1)}(k)=\left(1-e^{a}\right)\left(x^{(0)}(1)-\frac{u}{a}\right)e^{ak}\qquad(k=0,1,2\cdots)$$

Eq. (12) and (13) are called the time response models of GM (1, 1), and they are the calculation formulas of grey forecasting models GM (1,1). And –a uncover the evolving dynamics of $\hat{x}^{(1)}$ and $\hat{x}^{(0)}$.

Data Analysis and Results Discussion

Data Sources and Data Processing

Wind speed plays a vital role in the wind resource assessment, because the wind power is directly proportional to the cube of the wind speed. Data analysis provided in this paper is based on the record of offshore wind towers of Dafeng in Jiangsu Province of China in 2008. Because a lot of wind farms were established in Dafeng region of China to develop and exploit wind energy resources. Dafeng is located in the east of Jiangsu Province of China (32°56'~ 33°36' N, 120°13 '~ 120°56' E), east to Yellow Sea, and has 112 kilometers of coastline. Dafeng is a treasure trove of coastal area and has 10 million hectares wetland which is the largest in Asia according to the world's important wetlands list of the United Nation. Specific location of the area is shown in the Figure 1.

Fig.1. Dafeng location on the map

The tower locations have an altitude of 85 meters (from mean sea level). Observation data contains a one year (2008) record of hourly mean wind speed, wind direction, maximum gust speed and etc. Wind speed are sampled every 500 milliseconds, from which a mean wind speed of every one hour are calculated. Then, these are all averaged in each hour to get the one hourly value. The wind speed data is the mean value of every hour.

Table 1 indicates the hourly average wind speed that is measured every an hour of 24 hours on Jan.1st, 2008. The first column indicates the number of days, the first row indicates the continuous 24 hours, and 0 is the starting time. The second row indicates the measurement data of the wind speed.

Table1. The measurement data of wind speed

Date 2008 01.01	Time	0	1	2	3
	v	13.87963	11.63439	12.11099	12.15045
	Time	4	5	6	7
	v	12.24097	13.19287	12.61346	14.25703
	Time	8	9	10	11
	v	14.35235	15.398	13.80326	14.38727
	Time	12	13	14	15
	v	14.16288	13.67787	13.4981	12.24357
	Time	16	17	18	19
	v	11.06982	11.32077	11.6538	10.30227
	Time	20	21	22	23
	v	10.29709	11.34727	10.85774	11.4501

Data in the Table 1 is processed according to the steps in section 2. The predicted wind speed $\hat{x}^{(0)}(k)$ can be drawn in the Table2. In the paper, five consecutive time-series data sets of wind speed are chosen for the grey forecasting model GM (1, 1). The predictive values of the hourly average wind speed were obtained one hour before their actual value measured. The average wind speed of the next one hour would be predicted through the measurement data of the previous five hours.

As a result, there are 23 predicted data whose time are set to 1 - 23. Additionally, based on the method mentioned above, the predicted data with the time of 1- 4 are derived from the measurement data with the time of 0 – 4 which are the initial data, and the predicted data with the time of 5- 23 are obtained by their previous five different measurement data.

Table2. The predicted wind speed

Date 2008 01.01	Time	0	1	2	3
	$\hat{v}$	13.87963	11.7583	11.9402	12.1249
	Time	4	5	6	7
	$\hat{v}$	12.3125	12.5029	13.2924	13.1388
	Time	8	9	10	11
	$\hat{v}$	14.5143	14.9442	16.3709	13.8992
	Time	12	13	14	15
	$\hat{v}$	14.1188	13.6592	13.8606	13.1601
	Time	16	17	18	19
	$\hat{v}$	11.9902	10.5410	10.1812	11.1873
	Time	20	21	22	23
	$\hat{v}$	10.6163	9.8378	10.6604	11.6813

In the Table 2, the data of header, the first column and second row represent the same meaning as the Table 1. The data in the Table 1 are used as the gray prediction model inputs. According to the Eq. (3), a new series is obtained which has weakened randomness, strengthened regularity. Then, the model was made by using the new generated series. According to the Eq. (8), the model's main parameters 'a' and 'u' are calculated. Substituting these two parameters into the Eq. (12) and (13), the target data is calculated, respectively. $\hat{x}^{(0)}(k)$ is the computation results of Eq. (13), which is different from the predicted values $\hat{x}^{(0)}(k+1)$ of Eq. (13). If k=0, $\hat{x}^{(0)}(0)$ is equal to the initial values which couldn't be predicted and are shown in the Table 2. However, from the second element of the sequence, they could be predicted through the grey system prediction models and their predicted values are $\hat{x}^{(0)}(1)$, while there is k=0 in the Eq. (13). Therefore, the Eq. (13) corresponds with the Table 2.

The comparison between the wind speed predicted by the grey system theory model and hourly mean wind speed measured in Dafeng is shown in the graph of Fig.2. Because the values are the same, there is no significance difference between them at the starting time point 0. Therefore, the last 23 groups' data are taken for comparison. A total number of datasets in one day are presented, of which predicted and actual values are indicated by different Line and point. This shows that wind speed values predicted by the grey theory model are very close to the measured values for the all datasets. These ranges of error are normally considered as acceptable for the weather data prediction.

The error values in estimating the wind speed are shown in Fig.3. When there is an inflection point, there is a maximum deviation between the predicted value and measured value of wind speed, which means that the bigger absolute value on the inflection point is, the bigger error value in estimating wind speed is, such as the point of time 10 and 18. The largest deviation is 2.56m/s at the time 10.

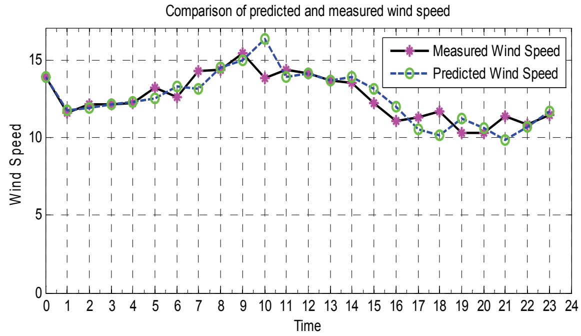

Fig. 2. Comparison between the grey forecasting wind speed and the measurement wind speed in Dafeng

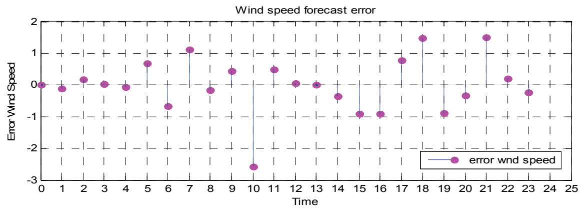

Fig. 3. Error values between the predicted and measured wind speed

Wind Power Density and Comparison

Wind speed forecasting is an estimate method for the future wind speed. Therefore, it also has the disparity with the objective reality and this disparity is the prediction error [16]. Prediction error and prediction accuracy is closely related. If the error is bigger, the accuracy is lower, and otherwise, if the error is smaller, the accuracy is higher [17]. Obviously, the research on the causes of errors, calculating and analyzing the size of the error is very significant [17]. The prediction error not only shows the prediction accuracy of the results when making decisions to offer an important reference, but also is for the improvement of wind speed forecasting, testing and selection of appropriate methods for prediction.

Many methods and indicators could be applied for the calculation and analysis of errors. Furthermore, there are mainly two methods which are relative error "e" and mean absolute percentage error (MAPE), root mean square errors (RMSE), and they can be expressed as in the following equations:

(14) $$e=\frac{X-\hat{X}}{X}\times 100\%$$

(15) $$\text{MAPE}=\frac{1}{n}\sum_{i=1}^{n}\frac{\left|X-\hat{X}\right|}{X}\times 100\%$$

(16) $$RMSE=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(X-\widehat{X}\right)^2}$$

By applying the grey prediction model, the wind speed is calculated and compared with the results obtained from actual wind speed. The error analysis results are shown in the Table 3. When calculating the mean absolute percentage error (MAPE) and root mean square errors (RMSE), the 23 predicted data is divided into three parts. The first part is the data sets with the time 1 – 7 and there are 7 data, and beside that, the second and the third parts are the data sets with the time 8 – 15 and 16 – 23 respectively, and they all have 8 data. In the 23 predicted data, the maximum relative error is 18.6%, the minimum is 0.21%, and there are only 3 data whose relative errors are more than 10%. Additionally, the MAPE of three parts are 3.43%, 4.41% and 7.22% respectively, the maximum RMSE is up to 1m/s, and the average RMSE of 23 predicted data is less than 1m/s.

Table3. Error of hourly predicted wind resource power density

	Time	0	1	2	3	MAPE(%)	RMSE
Date 2008 01.01	e(%)	0	-1.07	1.41	0.21	3.43	0.5654
	Time	4	5	6	7		
	e(%)	-0.58	5.23	-5.38	7.84		
	Time	8	9	10	11	4.41	1.0023
	e(%)	-1.31	2.95	-18.6	3.39		
	Time	12	13	14	15		
	e(%)	0.31	0.14	-2.69	-7.49		
	Time	16	17	18	19	7.22	0.9273
	e(%)	-8.31	6.89	12.63	-8.59		
	Time	20	21	22	23		
	e(%)	-3.1	13.3	1.82	-2.02		

Conclusion

Short time wind speed prediction has been done for the Dafeng region by using the grey forecasting models and wind speed data obtained from a meteorological tower. Through the comparison with the measured value of wind speed, the predicted value can afford a clear picture of wind speed. It is found that the error between the measured and predicted value of wind speed is small, so it can be used for the short time wind speed prediction. Wind power safety and effectiveness output in wind farms that strongly depends on the wind speed. The study in this paper has shown that the short-term (hourly-level) wind speed prediction based on the gray theory has certain significance especially for operation of wind power plants and power systems.

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