An estimation method of the fault wind turbine power generation loss based on correlation analysis

Tao Zhang $^{1,2,3}$, Shourang Zhu $^{1,2}$, Wei Wang $^{1,2}$

$^1$NARI Group Corporation (State Grid Electric Power Research Institute), Nanjing 211000, China
$^2$NARI-TECH Control Systems Ltd., Nanjing 210061, China

E-mail: linyurong@163.com

Abstract. A method for estimating the power generation loss of a fault wind turbine is proposed in this paper. In this method, the wind speed is estimated and the estimated value of the loss of power generation is given by combining the actual output power characteristic curve of the wind turbine. In the wind speed estimation, the correlation analysis is used, and the normal operation of the wind speed of the fault wind turbine is selected, and the regression analysis method is used to obtain the estimated value of the wind speed. Based on the estimation method, this paper presents an implementation of the method in the monitoring system of the wind turbine, and verifies the effectiveness of the proposed method.

1. Introduction

With the development of wind power industry in China, more and more attention has been paid to the study of the economic benefit of wind power. The study of literature [1] shows that the wind turbine failure rate has an important influence on the economic benefit of wind farm. In order to measure the influence, it is necessary to obtain the estimated value of the power generation lost during the wind turbine failure.

2. Problems in the estimation of loss of power generation

According to the theory of wind energy conversion and Bates theory in [2], the active power $W$ of wind turbine is:

$$W = \frac{1}{2} C_p \rho S v^3$$

(1)

where $\rho$ represents the air density, $S$ stands for the wind turbine swept area, $v$ is wind speed, and $C_p$ indicates the wind energy utilization coefficient. From equation (1), it can be found that the relationship between active power and wind speed is cubic, and it is closely related to the wind sweep area, air density and wind energy utilization coefficient. The blade angle of wind turbine will change with the change of wind speed, which will affect the power coefficient of wind turbine, and the air density will change with time. So it is very difficult to estimate the theoretical output power of the fault wind turbine by Eq.(1).

The initial approach to estimating the power loss of the fault generator is to refer to the normal operation of the wind turbine to estimate the power generation; or to estimate the average wind speed
of the wind farm during the outage period and then calculate the power generation capacity. Literature [3] points out that these two methods are easy to implement, but have great error.

With the help of the Weibull distribution of wind speed and wind turbine output power curve in [4], another researchers present an estimation method for wind turbine power generation in [3] and [5], respectively. In [3], the proposed method uses wind tower wind speed as a fault wind turbine speed estimates, and combined with the wind turbine theory output power curve to estimate the power loss. In the literature [5], based on the analysis of the shortcomings of the methods mentioned in the literature [3], the average value of the wind speed of two normal running wind turbines which is nearest to the fault is taken as the wind speed estimation value of the fault wind turbine, and combined with the actual output power curve of the wind turbine to estimate the loss of power generation.

The research of literature [5] has shown that it is reasonable to estimate the loss of power generation by using the actual output power curve of the wind turbine rather than the theoretical output power curve, but in the estimation of wind speed it is simple to use the average value of the wind speed of two normal running wind turbines. Wind speed is affected by terrain, climate, season and other factors. Therefore, the wind speed estimation method is only based on the geographical distance, although there is a certain rationality, but the lack of a strong theoretical basis.

3. Problems in the estimation of loss of power generation

In view of the shortcomings of the proposed method of [5], this paper presents a method to estimate the power generation loss of fault wind turbine. This method is mainly studied in the aspect of wind speed estimation, and an estimation method based on correlation analysis is put forward.

This section will begin with a general description of the estimation method of the loss of wind power generation in this paper. Through the above analysis, it is not difficult to see that the wind speed and the output power curve are the two factors to estimate the loss of power generation. Due to the failure of the wind turbine wind speed is not available, the wind speed of the fault wind turbine must be estimated first, and then combined with the output power curve to obtain the estimated loss of power generation.

In terms of the output power curve will continue to use the research results of the literature [5], namely the use of the actual output power curve. The fitting method and process of the actual output power curve is not the focus of this paper, and the literature [5] has been introduced in detail. The actual output power curve of the fault wind turbine is given directly, which can be described by the following formula according to literature [6]:

\[
P_G(v) = \begin{cases} 
0 & v < v_S \\
f_1(v), & v_S < v \leq v_1 \\
... & \\
f_k(v), & v_k < v \leq v_E \\
0 & v > v_E 
\end{cases}
\]  

(2)

where \(v_S\) is cut-in wind speed, \(v_E\) is cut-out wind speed, \(v_1, v_2, \ldots, v_k\) are actual wind speeds when the power curve fitting is performed, and \(f_1, f_2, \ldots, f_k\) are curve functions corresponding to each.

Suppose the fault start time of wind turbine \(G\) is \(t_1\), and the fault end time is \(t_2\). The estimated value \(\hat{K}_G\) of the electric energy in the wind turbine \(G\) fault period can be obtained by the following formula:

\[
\hat{K}_G = \int_{t_1}^{t_2} P_G(\hat{v}_G(t))dt
\]  

(3)

where \(\hat{v}_G(t)\) stands for estimated value of wind turbine speed during its fault period.

According to the study of [7], \(f_1, f_2, \ldots, f_k\) can be described by polynomial. Therefore formula (3) of the integral calculation is feasible.
The following two sections will be discussed in the acquisition of another element $\hat{v}_G(t)$.

4. Wind velocity correlation
Correlation analysis theory has been applied to many fields of power system according to literature [8] and [9]. In the clean energy field, the correlation analysis is applied to the power prediction by [10].

In this paper, the correlation analysis theory is used to the wind speed estimation of fault wind turbine.

By means of correlation analysis, the normal operation wind turbine whose wind speed has a strong linear correlation with the wind speed of fault wind turbine is selected. Then wind speed of fault wind turbine will be estimated by this selected wind turbine.

The Pearson correlation coefficient is proposed as a measure of the correlation between two wind speeds and in different wind turbines, which is based on the research of [11]. Pearson correlation coefficient is a linear correlation coefficient which reflects the degree of correlation between the two variables. The Pearson correlation coefficient $r$ of any two wind turbine $A$ and $B$ can be defined as:
Where $q$ represents the number of wind speed values, $v_{Ai}$ and $v_{Bi}$ are two wind turbine wind speed values. Accord to the formula (4), the range of $r$ is between -1 and 1. If the $r$ is positive, it indicates that the wind speed of two wind turbine is positively correlated, that is, the wind speed of a wind turbine becomes larger, and the wind speed of the other wind turbine becomes larger. If the $r$ is negative, it indicates that the wind speed of two wind turbine is negatively correlated, at this time, if the wind speed of a wind turbine becomes larger, the wind speed of the other wind turbine will become smaller.

When the absolute value of $r$ is 1, the wind speed of two wind turbine is completely linear correlation. When the absolute value of $r$ is zero, the wind speed of two wind turbine is completely linear correlation. When the absolute value of $r$ is between 0 and 1, there is a certain linear relationship between the wind speed of two wind turbines. The absolute value of $r$ closer to 1, it shows that the closer the linear relationship. Generally, when the absolute value of $r$ is between 0.7 and 1, we can think of a strongly linear correlation between the wind speed of two wind turbines.

By the above analysis, the acquisition of the correlation coefficient between the wind speeds of two wind turbines depends on the wind speed history data. Wind turbine monitoring system has stored all the running data of the wind turbine, including the wind speed. So it is very convenient to realize the correlation analysis of the wind speed in the wind turbine monitoring system.

Figure 1 shows the implementation of the specific process. Eventually each wind turbine will get a list of wind turbines that are linearly related to its wind speed. The wind turbines in the list can be arranged in the order of the absolute value of the Pearson correlation coefficient.

5. Wind speed estimation

The research of literature [12] describes a regression analysis method based on correlation coefficient. When there is a close linear relationship between the two sequences of variables, a sequence of variables can be calculated by another sequence of variables using the regression equation. According to this method, a wind speed estimation method is designed in this paper.

The analysis in the previous section shows that the linear correlation degree between the wind speeds of two wind turbines can be reflected by the Pearson coefficient. When the wind turbine $G$ fails, the normal operation wind turbine $N$ which has the absolute maximum value of the Pearson coefficient can be selected from the list of wind turbines. In the time of failure of the wind turbine $G$, the wind speed sequence of the wind turbine $N$ can be measured. The regression analysis method is used to analyze the wind speed sequence of the wind turbine $N$, and the wind speed estimation values in the wind turbine $G$ fault time period can be obtained.

It is still assumed that the fault start time of the wind turbine $G$ is $t_1$, and the fault end time is $t_2$. $\hat{v}_G(t)$ is the estimation value of wind speed of wind turbine $G$ during its fault period. $v_N(t)$ is wind speed of wind turbine $N$. According to the regression equation, we can get:

$$\hat{v}_G(t) = a + bv_N(t)$$

where $a$ and $b$ stand for correlation coefficient, their acquisition depends on the historical wind speed data as same as Pearson correlation coefficient calculation demand. Specific as follows:

$$b = \frac{\sum_{i=1}^{q} (v_{Ni} - \bar{v}_N)(v_{Gi} - \bar{v}_G)}{\sum_{i=1}^{q} (v_{Ni} - \bar{v}_N)^2}, \quad a = \bar{v}_N - b\bar{v}_G$$
where \( q \) is the number of historical wind speed data, \( \bar{v}_N \) and \( \bar{v}_G \) stand for the average value of wind speed. That there is:

\[
\bar{v}_N = \frac{\sum_{i=1}^{q} v_{Ni}}{q}, \quad \bar{v}_G = \frac{\sum_{i=1}^{q} v_{Gi}}{q}
\]  
(7)

By means of equation (5) and equation (7), the estimated value of the wind speed of the fault wind turbine can be obtained. At this point, the wind speed estimation of the two elements of the fault generator loss estimation is solved.

6. Implementation and validation of the estimation method

A remote centralized monitoring system for wind farm has been built by SPIC JIANGSU NEW ENERGY CO. LTD in Yancheng City, Jiangsu province, CHINA. In order to validate the proposed method for estimating the loss of wind power generation, the proposed method is applied to the remote centralized monitoring system, and the Zhengdong wind farm is selected as the experimental object.

First of all, the research of wind speed correlation is verified by experiment. Table 1 presents the Pearson correlation coefficient between five wind turbines. The historical data used in the calculations are from March 2015. This five wind turbines are located on one collector line, and are in a zigzag arrangement.

Table 1 shows that the biggest Pearson correlation coefficient of wind speed with the wind turbine \( B_2 \) is wind turbine \( B_4 \), and the biggest Pearson correlation coefficient of wind speed with the wind turbine \( B_3 \) is wind turbine \( B_5 \). It can be seen that the wind speed correlation of the strongest two wind turbines may not be the most recent. In the following experiments, the wind turbine \( B_2 \) is supposed as the fault wind turbine.

|      | B1   | B2   | B3   | B4   | B5   |
|------|------|------|------|------|------|
| B1   | 1.000| 0.905| 0.853| 0.872| 0.771|
| B2   | 0.905| 1.000| 0.881| 0.912| 0.798|
| B3   | 0.853| 0.881| 1.000| 0.894| 0.907|
| B4   | 0.872| 0.912| 0.894| 1.000| 0.909|
| B5   | 0.771| 0.708| 0.907| 0.909| 1.000|

Figure 2 shows the actual curve of the wind turbine \( B_2 \) and \( B_4 \) wind speed from 0 to 12 April 1, 2015. The dark curve is the \( B_2 \) wind speed, and the light curve is the \( B_4 \) wind speed. From the figure can be seen in about 1 to 3 hours, 4 to 7 hours, 8 to 10, 11 to 12 hours, and so on, the two curves have the same trend.
The fault is assumed to occur on the wind turbine $B2$ in this period of time. According to the wind speed of the wind turbine $B4$ and the formula (5) to the formula (7), the estimated wind speed of the wind turbine $B2$ during this period of time is calculated. Figure 3 shows the comparison between the actual wind speed and the estimated wind speed of the wind turbine $B2$.

The dark curve in Figure 3 is still the actual wind speed of the wind turbine $B2$, and the light curve is the estimated wind speed of the wind turbine $B2$ obtained by the method of the wind speed estimation in this paper. From the graph we can see that the curve of wind speed estimation is consistent with the actual curve.

7. Concluding remarks
In this paper, an in-depth study on the estimation of loss of power generation of wind turbine during its fault period is presented, and a method based on correlation analysis is employed. In this method, by analyzing the correlation of wind speed between wind turbines, the normal operating wind turbine which has a strongly linear correlation of wind speed with the fault wind turbine is selected. Then by using the wind speed of the normal operating wind turbine, the fault wind turbine wind speed can be estimate by according to regression analysis method, and combined with the actual output power curve, the loss of power generation is estimated. The experimental results show that the method is accurate and effective.

References
[1] Gao Yang 2014 Analysis of wind power generation capacity Science and Technique Information 3 p 220
[2] Yang Gang and Chen Ming 2008 An effective method for calculating power generation quantity for wind turbines East China Electric Power 36 p 12
[3] Liu Changhua 2010 Calculating method of power generation loss by wind generating set outage based on excel INNER MONGOLIA ELECTRIC POWER 28 p 27
[4] Lv Dong 2012 Discussion and practice of a fast method for calculating the generating capacity of the wind turbine Science & Technology Information 25 p 55
[5] Zhang Tao, Zhu Shourang, Wang Wei, et al. The Research on an Estimation Method of Power Generation Loss of the Fault Wind Turbine Jiangsu Electrical Engineering 34 p 30
[6] Boettcher F, Peinke J, Kleinhans D, Friedrich R 2007 Handling system driven by different noise sources: implications for power curve estimations Wind Energy, Springer p 179
[7] Kang M S. 2007 Generation cost assessment of an isolated power system with a fuzzy wind power generation model IEEE Trans on Energy Conversion 22 p 394
[8] Li Wei, Bi Tianshu, Yang Qixun 2011 Fault Phase Selection with Fault Component in same-tower Double-circuit Lines Based on Correlation Analysis Automation of Electric Power Systems 35 p 58
[9] Li Yan, Chen De shu, Yuan Rong xiang 2003 Study on simulation and improvement of transient current differential protection based on correlation analysis RELAY 31 p 64
[10] Wang Yinsong and Su Ziqing 2015 A Prediction Method for Wind Speed Based on the Adjacent Wind Power Generator Measured Data Correlation Analysis Journal of North China Electric Power University 42 p 91
[11] Kusiak A. and Li W Y. 2010 Estimation of wind speed: A data-driven approach Journal of Wind Engineering and Industrial Aerodynamics 98 pp 559-567
[12] Jiang Shufa 1999 Application of correlation coefficient in regression analysis Journal of Shanghai Institute of Electric Power 15 pp 34-39