Research on Yaw Deviation of Wind Turbine Based on Dynamic Time Warping

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Abstract. The yaw deviation is common in the process of wind turbine generation. Excessive wind deviation will cause a series of problems, such as the reduction of wind turbine generating efficiency, the wear of main shaft, gearbox failure. In this paper, a wind deviation detection algorithm based on dynamic time warping is proposed by using data in supervisory control and data acquisition (SCADA) of wind turbine. Through dynamic time warping (DTW), the wind speed is divided into three sections: ascending, descending and stationary. Then the wind deviation is obtained by fitting the function of wind angle and power. Compared with the traditional algorithm, the wind deviation detection algorithm proposed in this paper is more stable and accurate.

1. Introduction

Yaw system is an important part of wind turbine. Its function is to make the engine room of wind turbine face the direction of wind, make full use of wind energy, and improve the efficiency of power generation. Accurate measurement of wind direction is the prerequisite for the effective function of yaw system. Due to the cost problem, most of the current wind turbines are not equipped with laser wind radar, and the wind vane installation, turbulence and electrical measurement caused by static deviation and wind turbulence and yaw system response delay caused by the dynamic deviation, make the wind deviation widely exist in the wind turbine. The research object of this paper is the static wind deviation.

Figure 1 is the wind turbine deviation diagram, and \( \theta \) is the wind deviation. When the engine room is facing the incoming wind direction, the wind deviation is zero, and the utilization rate of wind energy is the highest. When the yaw deviation is large, the generating efficiency of wind turbine is lower. When the wind deviation exceeds 10°, the generating power of the unit will be reduced by about 4.5%[1]. In addition, the windage deviation usually exists in one direction, which causes the unit to suffer from one-way force deviating from the central shaft. Long term operation will cause problems such as wear of main shaft and gearbox failure, which will seriously affect the service life of the unit and cause economic losses. Therefore, it is of great significance to detect the wind deviation
of wind turbine and correct the deviation in time to improve the power generation efficiency, prolong the service life of the unit and increase the economic benefits.

Figure 1. Principle of yaw deviation of wind turbine

In the past, the research on yaw wind deviation mainly focused on the control strategy of yaw system[2-3], which did not consider the deviation of sensor itself, and ignored the performance difference between different units in the same wind field. With the development of data science, the methods of analyzing yaw wind deviation from the perspective of data appear continuously[4-5], but the performance difference of the same unit under different wind conditions, such as the time series change mode of wind speed, has not been considered, which affects the accuracy of yaw wind deviation calculation. In view of the existing problems, this paper proposes a wind deviation detection algorithm based on dynamic time warping based on wind turbine SCADA data, and gives the principle and steps of the algorithm. An example of wind turbine in a wind farm shows that this method can effectively detect the wind deviation.

2. Main algorithm principles

The algorithm used in this paper can be divided into two parts: one is dynamic time warping(DTW), the other is curve fitting of wind deviation angle. By comparing the time series data of wind speed with the set standard state, the wind speed is divided into three states: rising, steady and falling. After the wind speed is divided into different states, the data are divided into different warehouses, and the curve fitting of the data in each bin is carried out to obtain the wind deviation angle.

2.1. Dynamic time warping

Dynamic time warping (DTW) distance is a distance measurement method for similarity matching of sequence points in time series by bending time axis. DTW was first used to process text and language data, and then it has been widely used in time series similarity measurement. DTW does not limit the calculation of the distance between corresponding points. It can deal with the distance calculation of unequal length time series, and can also deal with the translation and bending of time series in a certain range on the time axis. It is not sensitive to the sudden change and abnormal points of time series. Therefore, it can better match the morphological similarity of time series, and is widely used in time series similarity measurement and time series module. The problems of pattern recognition, time series data classification and clustering are discussed. Figure 2 is a schematic diagram of DTW distance measurement.
For two time series $Q = \{q_1, q_2, q_3, ..., q_m\}$ and $C = \{c_1, c_2, c_3, ..., c_n\}$, the goal of DTW algorithm is to find the optimal regularization path and get the minimum regular distance $DTW(Q, C)$. The regular path satisfies the boundary conditions, continuity conditions and monotonicity conditions, which can be expressed as $W = \{w_1, w_2, w_3, ..., w_p\}$, where $w_k = (i_k, j_k)$ represents the $i$-th point of the first time series and the $j$-th point of the second time series. The optimization problem of DTW can be expressed as follows:

$$DTW(Q, C) = \min_{W} \sum_{k=1}^{p} d(i_k, j_k)$$  \hspace{1cm} (1)

Where $d(i_k, j_k)$ is the bending distance between $q_k$ and $c_k$. In order to solve the above equation, the dynamic programming method is usually used:

$$D(i, j) = d(i, j) + \min\{D(i-1, j), D(i, j-1), D(i-1, j-1)\}$$ \hspace{1cm} (2)

Where $D(m, n)$ is the minimum regularization distance of DTW optimal regularization path, that is, $DTW(Q, C) = D(m, n)$.

Based on the principle of DTW, using the wind speed data in SCADA, the state of wind turbine is divided into three types: wind speed rising, wind speed decreasing and wind speed stable. Then the wind deviation of wind turbine is calculated in each state.

### 2.2. Calculation of yaw deviation

The deviation of yaw angle to wind is mainly reflected in whether the maximum point of wind angle power curve deviates under the same wind speed. When the wind angle is positive or negative, the maximum value is taken at 0° and when there is positive or negative deviation, the corresponding wind angle power curve reaches the maximum value at positive or negative value. Figure 3 shows the corresponding relationship between the yaw deviation and the maximum value of the wind direction-power curve.

It is generally considered that there is a parabola relationship between the power curve and the angle of wind deviation. After the wind speed is divided into different compartments, if the wind speed is small enough, it can be considered that the influence of wind speed in the same wind bin on
the active power is the same, and then it can be assumed that there is a quadratic function relationship
between the power and the wind deviation:

\[ P = a + b * (x - c)^2 \]  (3)

Where \( P \) is the active power, \( x \) is the wind angle, \( a \) and \( b \) are constants, and \( c \) is the yaw deviation.
In this way, as long as the amount of data is enough, the above quadratic function can be fitted, and then the yaw deviation angle in the wind bin can be obtained.

3. Algorithm flow

3.1. Extraction of data from SCADA

The main algorithms used in this paper, whether dynamic time warping or wind deviation fitting, are based on a large number of data. The extracted data include time, active power, wind speed, wind angle, pitch angle and unit state parameters, such as operation, shutdown, power limit, etc.

3.2. Data preprocessing

Data preprocessing includes data cleaning and data denoising.

The purpose of data cleaning is to eliminate abnormal data, such as shutdown, power limit, sensor failure and so on. At the same time, in order to avoid the influence of pitch angle change on power, it is necessary to select the data of power climbing stage for analysis.

Data de-noising is to reduce the burr caused by noise in the data. The method adopted in this paper is moving average noise reduction. According to the fluctuation amplitude of other sampling points near a measurement point, the amplitude of this point is modified, so as to make the vibration curve smooth enough to achieve the purpose of noise reduction. The moving average formula is as follows:

\[ y_i = \frac{1}{N} \sum_{n=0}^{N-1} x_{i-n} \quad i = 1, 2, \ldots, m \]  (4)

Where \( x \) represents the data value obtained by sampling, \( y \) represents the data after smoothing, \( m \) represents the total number of measurement data. \( n \) is the average number of points. In this paper, five points are taken for sliding average, that is, \( n \) is equal to 5.

3.3. Dividing wind turbine state

Based on the dynamic time warping principle mentioned above, the wind turbine is divided into three stages: wind speed rising, wind speed stabilizing and wind speed decreasing. In the specific calculation, it is necessary to set three kinds of standard wind speed rise, steady and fall stages, and then select the time window sliding to calculate the wind speed data in the time window. The minimum distance from the standard state will determine which state it belongs to.

3.4. Dividing wind speed

In the power ramp stage, wind speed is divided into continuous data warehouse with \( w \) width. Because we assume that the quadratic function of power and wind deviation is based on the premise that the influence of wind speed on power under the same wind bin is the same, so the narrower the wind speed bin is, the smaller the \( w \) is, the better. However, the smaller the \( w \) will cause the less data under each wind bin, which is not conducive to function fitting. Therefore, the size of \( w \) should be determined according to the specific situation.

3.5. Fitting function

In the divided wind speed bin, the wind angle and active power are input into formula 3, and three constants \( a, b \) and \( c \) are obtained by fitting, where \( c \) is the yaw deviation angle of wind turbine.
3.6. Weighting results

According to formula 5 and formula 6, the wind deviation angle calculated under each wind speed bin is weighted and averaged to obtain the comprehensive deviation.

\[ \theta = \sum_{j=1}^{N} \omega_j \theta_j \]  

(5)

\[ \omega_j = \frac{v_j^3}{\sum_{j=1}^{N} v_j^3} \]  

(6)

\( v_j \) is the middle value of wind speed of each wind bin.

The weight selection takes into account the corresponding relationship between wind speed and power of wind turbine, which reflects that the contribution of yaw deviation in the wind bin is large when the wind speed is high.

In the same way, the yaw deviation angles obtained under the three states of wind speed rising, wind speed stable and wind speed decreasing are weighted average, as shown in the formula 7.

\[ \theta = \sum \gamma_i \theta_i \]  

(7)

The weight \( \gamma_i \) is the proportion of data volume of each state to the total data volume.

To sum up, the calculation flow of the proposed algorithm is shown in Figure 4.

![Figure 4. Algorithm flow chart](image)

4. Case study

Taking the calculation process of a 1500kW unit in a wind farm as an example, the data on 7S interval in June 2019 is stored in its SCADA, and the wind speed in the power climbing stage is 3.25-9.25m/s. After data preprocessing, the wind speed can be divided into three states: rising, stable and falling according to the wind speed. Fig. 5 shows the standard mode and DTW calculation results.
When dividing the wind speed bin, in order to consider the influence of wind speed on power and the requirement that the amount of data should not be too small, the width of 0.5m/s is selected. Next, the curve fitting of wind angle power data in each wind speed bin is carried out. Fig. 6 shows the fitting results of a certain wind bin.

The results of yaw wind deviation are calculated every 3 days, and the calculation results are shown in Fig. 7.
According to the analysis and calculation results, the average value of 10 calculation results of the unit in June 2019 is 7.04 degrees. The field inspection shows that the deviation of the unit is indeed existed, which shows that the method in this paper can calculate the yaw wind deviation of the unit. In addition, the standard deviation after DTW is 3.8, while the standard deviation of direct calculation results is 5.7, which shows that the stability of calculation results is better, which is more consistent with the situation that wind turbine yaw to wind deviation is similar in theory in the near time. The calculation results of other units are shown in Table 1.

| Number | Yaw deviation(°) Before DTW | Yaw deviation(°) After DTW | Standard deviation Before DTW | Standard deviation After DTW |
|--------|-------------------------------|-----------------------------|------------------------------|-------------------------------|
| 1      | 0.35                          | -1.24                       | 3.24                         | 1.81                          |
| 2      | -5.31                         | -4.41                       | 2.56                         | 2.15                          |
| 3      | -5.64                         | -5.35                       | 3.74                         | 2.25                          |
| 4      | -6.87                         | -5.84                       | 2.56                         | 2.32                          |
| 5      | 2.76                          | 3.02                        | 1.76                         | 1.58                          |
| 6      | -1.22                         | -2.88                       | 3.37                         | 2.69                          |
| 7      | 0.50                          | 0.67                        | 2.93                         | 2.03                          |
| 8      | -4.52                         | -4.25                       | 5.05                         | 4.31                          |
| 9      | 4.21                          | 4.30                        | 2.00                         | 1.45                          |
| 10     | 7.76                          | 7.04                        | 5.72                         | 3.85                          |
| 11     | -7.04                         | -7.11                       | 4.87                         | 3.67                          |
| 12     | 1.03                          | 0.96                        | 2.71                         | 2.22                          |
| 13     | -4.94                         | -3.61                       | 2.71                         | 2.46                          |
| 14     | 0.23                          | -0.30                       | 1.81                         | 1.55                          |
| 15     | 3.01                          | 2.57                        | 2.98                         | 1.96                          |
| 16     | -4.26                         | -4.33                       | 4.46                         | 3.17                          |

It can be seen that the standard deviation of the calculation results after dynamic time warping is significantly reduced, that is to say, the stability of the algorithm is improved. Through the dynamic time warping of wind speed, the wind turbine data is divided into three states: wind speed rising, wind speed stable and wind speed decreasing. Then the wind speed in different states is divided into three states, and the wind angle power curve in different sub warehouses is fitted. Finally, the wind deviation of wind turbine is obtained by weighted average. Through the actual comparison, the method proposed in this paper has the advantages of accuracy and stability.

5. Conclusion
This paper studies the yaw wind deviation of wind turbine, and proposes a calculation method based on dynamic time warping in the absence of lidar. Through the dynamic time warping of wind speed, the wind turbine data is divided into three states: wind speed rising, wind speed stable and wind speed decreasing. Then the wind speed in different states is divided into three states, and the wind angle power curve in different sub warehouses is fitted. Finally, the wind deviation of wind turbine is obtained by weighted average. Through the actual comparison, the method proposed in this paper has the advantages of accuracy and stability.
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References
[1] Wan S T, Cheng J f, Sheng X L. (2016) Analysis of Wind Turbine Power Oscillation Characteristics Based on the Equivalent Wind Speed. J. Noise and Vibration Control., 36: 127-132.
[2] Zou Q, Liu B F, Peng L, Wang J L. (2010) Application of Hill-Climbing Control Algorithm in Yaw Control System for Wind Power Generation Sets. J. Power System Technology. 34: 72-76.
[3] Wang X, Wu G Y, Pan D H, et al. (2020) Calibration Method of Wind Vane Measurement Error of Wind Turbine Based on Historical Operating Data. J. Acta Energiae Solaris Sinica., 41: 52-58.
[4] Xu J H, Guo P, Song P, Liu Y. (2019) Analysis and research on static deviation of the yaw system of wind turbines. J. Huadian Technology., 41: 1-9.
[5] Ouyang T H, Kusiak A, He Y S. (2017) Predictive model of yaw error in a wind turbine. J. Energy., 123: 119-130.
[6] Wu Z, Yu B. (2006) An algorithm for Dynamic Time Warping based on piecewise linear representation in Time Series. In: The 10th Annual Conference on enterprise informatization and industrial engineering. Beijing. pp. 387-391.
[7] Li C, Tian C H, Liu J Y, Cui P F, Jiang W. (2020) Research and application on yaw error detection of wind turbine yaw system. J. Renewable Energy Resources., 38: 620-624.