Study of the pitch behaviour of large-scale wind turbines based on statistic evaluation

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Abstract
Pitch control is a basic function of large-scale wind turbines to improve energy capture efficiency. Pitch system is also a component system with a high failure rate due to the complex pitch behaviour. It is helpful to the practical design and control if a clear pitch behaviour is obtained. However, pitch behaviour is affected by the structure of wind turbines, control strategies, wind resource characteristics, and so on. So, there is still a lack of sufficient understanding. In this study, the pitch behaviour of a 2 MW wind turbine is investigated based on SCADA data. Four key evaluation indicators describing pitch behaviour are proposed, which include pitch status, pitch time consumption, pitch angle peak, and mean pitch angle. Moreover, the SCADA data extraction algorithm for pitch behaviour investigation is also given. Then, the pitch behaviour is investigated based on statistical evaluation. Some valuable conclusions have been given. For example, for the investigated wind turbine, the time proportions for the four states (non-pitch, increasing pitch, pausing pitch, and decreasing pitch) are 85.80%, 5.97%, 1.45%, and 6.78%, respectively. The pitch cycles, pitch angle peak, and mean pitch angle increase with the increase of the standard deviation of wind speed.

1 | INTRODUCTION

With the rapid development of the wind power industry, the unit capacity of wind turbines is increasing, and the installation location is moving to more remote land and marine areas [1–3]. As one of the key technologies of large-scale wind turbines [4, 5], pitch technology has been widely used to reduce operation safety risks and improve wind turbine efficiency. After the use of pitch technology, once the wind speed exceeds the critical value, the wind turbines can adjust the blade pitch angle through the pitch system. On the other hand, the pitch system is a component system with high failure rates. According to the statistic investigations, the failure rate of the pitch system is about 42%, and 34% of the total downtime is due to the failure of the pitch system [6, 7]. Therefore, pitch behaviour has significantly impacted the safe operation, generation efficiency, and operation cost of wind turbines.

In order to obtain a clearer understanding of pitch load, Dai et al. established the theoretical analysis model of the pitch load [8, 9], Yang et al. studied the load prediction of the MEXICO rotor [10], Sang et al. [11] performed an experiment to investigate the effect of the diagonal inflow on the aerodynamic forces. For improving the blade structure design, Lee et al. optimized the blade pitch angle based on the BEM theory [12], Pavese and Verelst et al. reduced the flapping moment and the ultimate load of the blade [13, 14]. To optimize the pitch control system design, Erol carried out a robust delay dependent stability analysis of pitch control system [15], Pan et al. proposed a hybrid pitch control method [16], Shaimaa et al. employed a non-linear model predictive controller [17], Hamed and Saptarshi et al. developed the individual pitch control [18, 19], and Jia et al. [20] conceived a hybrid intelligent and adaptive pitch control. The above research works provide a theoretical basis for understanding the characteristics of the pitch system. However, since these
researches are mainly based on theoretical derivation, numerical simulation, and local experiments, they lack the support of actual field data. With the development of research, it is a new trend to make full use of supervisory control and data acquisition system (SCADA) data [21]. Many studies have focused on mining SCADA data to develop state monitoring, performance prediction and fault warning of wind turbines [22–29]. Some studies have also begun to use SCADA data to analyse the characteristics of pitch systems [30]. However, the study of pitch behaviour using SCADA data is still rare. For example, it has not been previously reported how to extract evaluation indicators of pitch behaviour from SCADA data. Thus, the systematic analysis and evaluation of the pitch behaviour is far from enough.

This paper aims to evaluate the pitch behaviour of wind turbines using SCADA data. Figure 1 shows the investigation scheme of the pitch behaviour, which shows the organizational logic of the research work. The remaining part is organized as follows. In Section 2, the control mode of the pitch system is introduced, including an overview of the pitch system, operational control of wind turbines, and operational control of the pitch system. In Section 3, the pitch behaviour based on statistic evaluation is investigated. Firstly, the pitch behaviour in a month based on raw SCADA data is analysed; subsequently, the data pre-processing for pitch behaviour analysis is studied, and the investigation of pitch behaviour is carried out. In this section, four key evaluation indicators describing the pitch behaviour are proposed, that is, the pitch status (non-pitch, increasing pitch, decreasing pitch, pausing pitch), the pitch time consumption of the pitch cycle, the pitch angle peak in the pitch cycle and the mean pitch angle in the pitch cycle. In Section 4, the influence of wind speed on the pitch behaviour is investigated. Finally, Section 5 ends the paper by summarizing the main conclusions.

2 | CONTROL MODE OF THE PITCH SYSTEM

2.1 | Overview of the pitch system

A 2-MW direct-drive wind turbine with a permanent magnet synchronous generator (PMSG) in a mountain wind farm in southern China is evaluated. The wind turbine generally includes the tower, nacelle, generator, wind rotor (hub and blades), and other parts. Each blade of the wind turbine is equipped with an electric-driven pitch system shown in Figure 2, which consists of a driving motor, a three-stage planetary reducer, and a blade [31]. When the wind reaches the target level, the pitch controller sends a pitch control command, the output torque of the driving motor passes through the transmission shaft, and the three-stage planetary reducer and finally is transmitted to the root ring of the blade root. Then, the blade rotates with the inner gear ring, which also changes the blade
TABLE 1 Parameters of the pitch system

| Components         | Parameters                  | Value |
|--------------------|-----------------------------|-------|
| Driving motor      | Rated output power (kW)     | 2100  |
|                    | Rated output torque (N·m)   | 37.5  |
|                    | Rated armature current (A)  | 38    |
| Planetary gear     | Efficiency                  | 94%   |
| reducer            | Reduction ratio             | 194.1 |
| Blade              | Tooth number of driving     | 14    |
|                    | pinion                      |       |
|                    | Tooth number of inner tooth | 141   |
|                    | ring                        |       |

pitch angle. The parameters of the pitch system are shown in Table 1.

As the current mainstream style, the 2 MW wind turbines have been equipped with a SCADA system, which can collect wind speed, output power, rotor speed, azimuth angle, blade pitch angle, and pitch motor current, and so on. The SCADA data of the wind turbine used for the statistical analysis is recorded in 2015. The sampling frequency of the used SCADA system is 1 Hz. Table 2 shows the parameter name and the raw data style of the SCADA system. The subsequent research is based on these SCADA data. For example, the analysis on wind speed distribution shows that its probability distribution follows the Weibull distribution, with a mean of 4.73 m/s and a standard deviation of 1.82 m/s. The wind speed distribution is shown in Figure 3.

2.2 Operational control of wind turbines

The relationship between the output power $P$ of the wind turbine and the wind speed $v$ is

$$ P = \frac{1}{2} \rho A C_p(\beta, \lambda) v^3 $$

where $\rho$ is the density of air; $A$ is the swept area of the wind rotor; $C_p$ is the wind energy utilization coefficient, which is a function of pitch angle $\beta$ and blade tip speed ratio $\lambda$, and

$$ \lambda = \omega R / v $$

where $\omega$ is the rotor speed of the wind turbine, and $R$ is the radius of the wind rotor [32]. Figure 4 shows the relationship between the power coefficient $C_p$ and blade tip speed ratio $\lambda$, with different pitch angles $\beta$.

The operation status of the wind turbine is typically divided into four stages, as shown in Figure 5 [31]. In Stage I, when the wind speed is below the minimum set wind speed, usually referred to as the cut-in wind speed, the wind turbine does not rotate and does not produce any output power. In this stage, the pitch system is not activated. In Stage II, the wind speed is
between the cut-in wind speed and the rated wind speed (the minimum wind speed that allows the wind turbine to produce the constant rated output power), the wind turbine generates and transmits power to the grid. In this stage, the pitch angle $\beta$ is usually near $0^\circ$ and keeps constant. The rotor speed $\omega$ of the wind turbine is controlled to ensure the tip speed ratio $\lambda$ is close to the optimal value so that the wind power coefficient $C_p$ reaches the maximum value, which means the wind turbine is running with the maximum wind energy utilization ratio. In Stage, when the wind speed is between the rated wind speed and the cut-out wind speed (the upper limit of the wind speed that allows the wind turbine to produce the constant rated output power), the wind turbine generates and transmits power to the grid, and the rotor speed is at the rated speed. In this stage, the wind turbine adjusts the power coefficient by changing the pitch angle. In Stage, when the wind speed exceeds the cut-out wind speed, the wind turbine shuts down and stops the power transmission to the grid. In this stage, the pitch angle $\beta$ increases from $0^\circ$ to $90^\circ$. Usually it also has a transition stage from Stage to Stage II. During this transition period, the pitch angle decreases from $90^\circ$ to $0^\circ$. The second and third stages are the effective power transmission stages, and the wind speed is between the cut-in wind speed and the cut-out wind speed. The pitch system is in a stationary state in the second stage and in an operating state in the third stage. Although the pitch system in the first and fourth Stages has a pitch process in which the pitch angle decreases monotonously from $90^\circ$ to $0^\circ$ and a feathering process in which the pitch angle increases monotonously from $0^\circ$ to $90^\circ$, the pitch system is not responding to the feedback control of output power [7].

### 2.3 Operational control of the pitch system

Figure 6 shows the variations of the wind speed, output power, and pitch angle of the wind turbine operation over a given time. The cut-in wind speed, rated wind speed, and cut-out wind speed of the wind turbine are 3.5, 11, and 25 m/s, respectively. The wind turbine has a rated output power of 2 MW and a rated rotor speed of 17 r/min [31]. The first part of Figure 6 (0–50 s) shows the wind speed is higher than the cut-in wind speed but lower than the rated wind speed, and the wind turbine is in the second stage. At this time, the motor of the pitch system is in a static state, and the pitch angle is close to $0^\circ$. The latter part of Figure 6 (50–275 s) shows the wind speed is high. When the wind speed reaches or exceeds the rated wind speed, the wind turbine is in the third stage. In the meantime, the pitch system is in the operating stage. At this stage, with the increase of wind speed, the motor of the pitch system is triggered, and the pitch angle increased. Once the wind speed is stable, the driving motor of the pitch system is suspended, and the pitch angle remains unchanged. As the wind speed continued to increase, the driving motor of the pitch system is triggered again, and the

### TABLE 2 Raw data style collected by SCADA system

| Time (h:m:s) | Wind speed (m/s) | Hub angle (rad) | Rotor speed (rad/s) | Current of driving motor 1 (A) | Current of driving motor 2 (A) | Current of driving motor 3 (A) | Angle of blade 1 (rad) | Angle of blade 2 (rad) | Angle of blade 3 (rad) | Output power (W) |
|-------------|------------------|----------------|---------------------|------------------------------|-------------------------------|-------------------------------|---------------------|---------------------|---------------------|-------------------|
| 14:20:01    | 3.5              | 2.03           | 0.78                | 7.78                         | 7.72                          | 5.38                          | 0.00                | 0.00                | 0.00                | 126,000           |
| 14:20:02    | 3.7              | 2.82           | 0.79                | 8.64                         | 5.9                           | 5.46                          | 0.00                | 0.00                | 0.00                | 133,000           |
| 14:20:03    | 3.8              | 3.60           | 0.79                | 8.46                         | 5.74                          | 6.16                          | 0.00                | 0.00                | 0.00                | 132,000           |
| ...         | ...              | ...            | ...                 | ...                          | ...                           | ...                           | ...                 | ...                 | ...                 | ...               |
| 18:39:01    | 6.2              | 4.13           | 1.37                | 12                           | 12.54                         | 10.36                         | 0.00                | 0.00                | 0.00                | 737,000           |
The pitch angle increases further. With the decrease of wind speed, the pitch system drives the motor to rotate in a reversed direction, and the pitch angle decreased. In this way, by adjusting the pitch angle, the rotor speed and output power of the wind turbine are kept comparatively stable to the rated value. The end section of Figure 6 (275–300 s) shows the wind speed decreased, and the pitch angle decreased to about 0°, and the pitch system returned to the static state again. Figure 6 presents relevant data variations in the operation process of the pitch system. The pitch system experienced two stages: stationary and running. In the running stage of the pitch system, there are rotation, pause, and reversal states.

3 PITCH BEHAVIOR BASED ON STATISTIC EVALUATION

3.1 Pitch behaviour analysis based on raw SCADA data

Figure 7 shows the variation of pitch angle in a month based on raw SCADA data. As illustrated in Figure 8, the pitch angle fluctuates with time and consists of a series of cycles. Here, the change period of the pitch angle from a static state (pitch angle approaching zero) to the next static state is called a pitch cycle, as shown in the sub-figure. Obviously, the length of the pitch cycle is related to the pitch time consumption. In a pitch cycle, there is a pitch angle peak, and a pitch angle mean. As can be seen from the sub-figure, the pitch control system generally operates in four pitch control states. In AB stage, the pitch angle is kept at the initial value, and the pitch system is in the non-pitch state. In addition, the initial value of the pitch angle is not 0° but has a certain offset β₀, which is determined by the aerodynamic performance of the blade. Usually, the initial pitch angle has the maximum wind energy capture efficiency. The BI stage means the pitch state. In this stage, the pitch angle fluctuates with time, and it can be divided into smaller stages. The variation of the pitch angle in this stage has the following characteristics: (1) it has an increasing pitch state, as shown in the CD stage, the pitch angle increases with time; (2) it has a decreasing pitch state, as shown in the EF stage, the pitch angle decreases with time; (3) it has a pausing pitch state, as shown in the GH stage, the pitch angle remains unchanged.

Through the above preliminary analysis, it can be found that the changes of the pitch angle are very complex. In order to describe the pitch behaviour of wind turbines in the wind farm, four evaluation indexes are defined as follows. In other words, in the following sections, pitch behaviour will be analysed from four dimensions.

- Pitch status (non-pitch, increasing pitch, decreasing pitch, and pausing pitch)
- Pitch time consumption of the pitch cycle
- Pitch angle peak in the pitch cycle
- Mean pitch angle in the pitch cycle
Since the raw SCADA data is sampled by 1 Hz, a large amount of data is saved, so it is necessary to extract the data related to pitch behaviour from the raw SCADA data. In addition, a quantitative description algorithm for the evaluation indexes of pitch behaviour is also required.

### 3.2 Data pre-processing for pitch behaviour analysis

The wind turbine investigated in this paper has three identical blades. Data obtained from one of the blades is used for analysis. According to the raw SCADA data analysis, four evaluation indexes are proposed to characterize the pitch behaviour. It can be pre-processed by following the steps.

1. **Data extraction from raw SCADA data**

   Influenced by wind turbine sensor system and other factors, SCADA raw data contains some null value, zero value, and abnormal value. In order to improve the accuracy of the analysis results, combined with the operating conditions and logs of wind turbines, the raw data need to be cleaned.

   - **Step 1:** Data with an output power of 0 or negative value in the process of shutdown or start-up should be eliminated.
   - **Step 2:** Eliminating the malfunction or abnormal operation data recorded in the operation log.
   - **Step 3:** Eliminating the data points recorded in the operation log for load-limited operation.

   After eliminating null values, zero values, and outliers, the resulting missing values affect the continuity of the data. It is necessary to fill in the missing values to ensure that the data is continuous in time. This paper uses the mean-value method to supplement the missing values. Taking the pitch angle $\beta_i$ as an example, the above-mentioned missing values due to null values, zero values, and outliers are filled as follows.

   \[
   \begin{align*}
   \beta_i = \beta_i, & \text{ is null} \\
   \beta_i = \frac{\beta_{i-1} + \beta_{i+1}}{2}, & \text{ otherwise}
   \end{align*}
   \]

   After the data cleaning, three different data sequences for wind speed, pitch angle, and output power are obtained from the pre-processed SCADA data.

   \[
   \begin{align*}
   v = (v_1, v_2, \ldots, v_i, \ldots, v_M) \\
   \beta = (\beta_1, \beta_2, \ldots, \beta_i, \ldots, \beta_M) \\
   P = (P_1, P_2, \ldots, P_i, \ldots, P_M)
   \end{align*}
   \]

   where $v_i$, $\beta_i$, $P_i$ ($i = 1, 2, \ldots, M$) are the wind speed, pitch angle, and output power of $i$-th moment, respectively. $M$ is the total amount of extracted data from the SCADA system.

2. **Data classification of pitch status**

   Four data subsets $D_0, D_1, D_2$, and $D_P$ are defined to correspond to states of non-pitch, increasing pitch, decreasing pitch, and pausing pitch during the operation of the pitch system, respectively.

   Data points are classified based on the following procedure.

   The changing rate of pitch angle at a certain moment is defined as

   \[
   \eta(t) = \frac{\beta(t) - \beta(t + T_i)}{T_i}
   \]

   where $T_i$ is the sampling period, which in this paper is 1 s.

   Considering the manufacturing assembly error, deformation, and measurement error of the pitch system. A criterion of the pitch angle is used to determine whether the pitch system of the wind turbine is in operation.

   \[
   \Gamma(t) = \eta(t - 2) \cdot \eta(t - 1) \cdot \eta(t)
   \]

   Defining $d_i = (v_i, \beta_i, P_i)$, four data subsets $D_0$, $D_1$, $D_2$, and $D_P$ can be classified as follows

   \[
   \begin{align*}
   d_i & \in D_0, \quad \Gamma(t) = 0 \text{ and } \beta \leq \beta_0 \\
   d_i & \in D_1, \quad \Gamma(t) > 0 \\
   d_i & \in D_2, \quad \Gamma(t) < 0 \\
   d_i & \in D_P, \quad \Gamma(t) = 0 \text{ and } \beta > \beta_0
   \end{align*}
   \]

3. **Calculation of pitch time consumption**

   Figure 8 shows the change of pitch angle in the $j$-th pitch cycle.

   In Figure 8, $s_i$ is the start sampling point of the pitch cycle, $s_k$ is the end sampling point of the pitch cycle, the time consumption of this cycle is

   \[
   T_j = (s_{j+k} - s_j) \cdot T_s
   \]

   where the subscript $j$ represents the $j$-th pitch cycle.

4. **Calculation of pitch angle peak and mean pitch angle**

   The pitch time consumptions are different in different pitch cycles, so the pitch angle peaks and mean pitch angles are also not the same in different cycles. According to Figure 8, the pitch angle peak in the $j$-th pitch cycle is

   \[
   \beta_{\text{max}} = \text{Max}(\beta_i, \ldots, \beta_{i+k})
   \]

   The mean pitch angle in the $j$-th pitch cycle is calculated as

   \[
   \beta_{\text{mean}} = \frac{1}{k}(\beta_i + \cdots + \beta_{i+k})
   \]

   Once all the data points have been processed, three datasets are obtained for pitch time consumption, pitch angle peaks, and
mean pitch angles for different pitch cycles.

\[
\begin{align*}
T &= (T_1, T_2, \ldots, T_N) \\
\beta_{\text{max}} &= (\beta_{\text{max1}}, \beta_{\text{max2}}, \ldots, \beta_{\text{maxj}}, \ldots, \beta_{\text{maxN}}) \\
\beta_{\text{mean}} &= (\beta_{\text{mean1}}, \beta_{\text{mean2}}, \ldots, \beta_{\text{meanj}}, \ldots, \beta_{\text{meanN}})
\end{align*}
\] (11)

where \(N\) is the total number of pitch cycles, that is, the number of operating times of the pitch system.

The total operating time of the pitch system can be calculated as

\[
T_\Sigma = \sum_{j=1}^{N} T_j
\] (12)

The mean pitch time consumption, the mean pitch angle, and the mean pitch angle peak of all the pitch cycles can be calculated using the following equations:

\[
\begin{align*}
\bar{T} &= \frac{1}{N} \sum_{j=1}^{N} T_j \\
\bar{\beta}_{\text{max}} &= \frac{1}{N} \sum_{j=1}^{N} \beta_{\text{maxj}} \\
\bar{\beta}_{\text{mean}} &= \frac{1}{N} \sum_{j=1}^{N} \beta_{\text{meanj}}
\end{align*}
\] (13)

Defining the number of data samples in data subsets \(D_0, D_1, D_D, \text{ and } D_P\) are \(M_0, M_1, M_D, \text{ and } M_P\), respectively, and the total number of data samples is \(M\), there are

\[
M = M_0 + M_1 + M_D + M_P
\] (14)

Then, the total normal operation time can be obtained as \(M \cdot \bar{T}_\Sigma\), and the respective proportions of the consumed time in four states of non-pitch, increasing pitch, decreasing pitch, and pausing pitch, are

\[
\begin{align*}
\tau_0 &= M_0 \cdot \bar{T}_\Sigma / T_\Sigma \\
\tau_1 &= M_1 \cdot \bar{T}_\Sigma / T_\Sigma \\
\tau_D &= M_D \cdot \bar{T}_\Sigma / T_\Sigma \\
\tau_P &= M_P \cdot \bar{T}_\Sigma / T_\Sigma
\end{align*}
\] (15)

Obviously,

\[
\bar{T}_\Sigma = \sum_{j=1}^{N} T_j = (M_1 + M_D + M_P) \cdot \bar{T}
\] (16)

### 3.3 Characteristics analysis of pitch behaviour

Figure 9 shows the proportions of pitch status (time spans) for non-pitch, increasing pitch, pausing pitch, and decreasing pitch stages of the pitch system. A total of 19,886,741 sets of data on the annual normal operation status of wind turbines are collected, which means that the yearly normal operation time of wind turbines is 5524.09 h (230 days), accounting for 63.06% of the annual time. Under normal operation, the time proportion in the stationary state of the pitch system is 85.80%, and the time proportion in the running state of the pitch system is 14.20%, and the total running time in the whole year is 48,875 s. The time proportions in pitch increasing state, pitch decreasing state, and pitch pausing state are 5.97%, 6.78%, and 1.45%, respectively. Obviously, the proportion of the pitch decreasing state time is higher than that in the pitch increasing state.

This is because: with the pitch angle increase, the blade aerodynamic load on the blade is the same as the rotation direction of the blade and provide dynamic torque; with the pitch angle decrease, the motor reverses, the aerodynamic load on the blade becomes the resistance moment [31].

According to the analysis, the longest pitch cycle lasted 936 s, and the shortest pitch cycle only lasted 2 s. The mean time consumption of all the evaluated pitch cycles is 37.19 s, with a standard deviation of 63.69 s. The frequency distribution of pitch cycles is shown in Figure 10. The following exponential
In each pitch cycle, the pitch angle varies based on wind speed. The mean pitch angle and the pitch angle peak are two important indicators to evaluate. Statistical analysis shows that the mean value of the mean pitch angles for all evaluated pitch cycles is 0.92°, with a standard deviation of 0.71°. Its frequency distribution is shown in Figure 11. The mean value of the pitch angle peaks for all evaluated pitch cycles is 1.87°, with a standard deviation of 2.26°. The frequency distribution is shown in Figure 12. The exponential distribution equations are used to fit the distributions of mean pitch angles, and pitch angle peaks are:

\[ f_{\beta_{mean}}(\beta_{mean}) = 0.872\left(\frac{\beta_{mean}}{1.0876}\right)^{0.0515}e^{-\left(\frac{\beta_{mean}}{1.0876}\right)^{0.9485}} \]  

\[ f_{\beta}(\beta_{max}) = 0.53\beta_{max}^{-0.53} \]  

As can be seen from Figure 12, the maximum value of the annual mean pitch angle is 2.54°. The pitch angle peak of the blade for all the evaluated pitch cycle does not exceed 25°. The pitch angle peaks in most pitch cycles are concentrated in the range of 0–25°, which probably indicates that the gear ring in the blade root bears a more frequent alternating load in this range.

4 | INFLUENCE OF WIND SPEED ON PITCH BEHAVIOUR

The variation of wind speed is the main factor that affects the pitch behaviour of wind turbines. Statistical analysis results of the collected wind speed data for the 12-month of 2015 are summarized in Table 3. It can be seen that the mean and the standard deviation of wind speed varied from month to month. In the 12 months, the mean values of wind speed varied from 3.42 to 5.53 m/s, with standard deviations varied from 1.27 to 2.04 m/s. Specifically, the wind speed in summer is comparatively low, and the mean value of the wind speed in June is the lowest, which is under 4.0 m/s. On the other hand, the wind speed in winter is higher than in other seasons, with the highest mean value in December, which is above 5.0 m/s. The variation coefficient (i.e. the ratio of the standard deviation to the mean value) of the wind speed ranged from 0.3–0.4, which indicates that wind speed varied significantly in each month.

Table 4 summarizes the pitch behaviours, including the proportion of pitch state time, number of pitch cycle, pitch angle peak, and mean pitch angle in each month. Generally, the non-pitch state time occupies most of the operating time of the wind turbine. In Table 4, it almost accounts for more than 80% of operating time except in December. The annual average proportion of increasing pitch is 5.97%, and that of decreasing pitch is 6.78%, and that of pausing pitch is 1.45%. The subtotal proportion of pitch state varied from 5.41% to 21.93%.

The monthly number of pitch cycles varied from 729 to 8553. December has the greatest number of pitch cycles, while June has the least number of pitch cycles. In particular, the proportion of pitch time is almost linearly increased with the increase of the number of pitch cycles. The monthly mean value of the consumed time of pitch cycles varies from 25.40 to 50.78 s, with the longest pitch cycle occurred in November, and the shortest pitch cycle occurred in August. The monthly mean value of the pitch angle peak varies from 1.37° to 2.44°, with the maximum value in November and the minimum value in August. The monthly mean value of the mean pitch angle varies from 0.86° to 1.47°, with the maximum value in November and the minimum value in August.

Based on data provided in Tables 3 and 4, the correlations between operating characteristic parameters and the wind speed are evaluated. The Pearson correlation coefficients are summarized in Table 5. It shows that: (1) The correlation coefficient between mean wind speed and the proportion of pitch time is about 0.91. (2) The correlation coefficient between mean wind speed and the number of pitches is about 0.87. (3) The correlation coefficients between mean wind speed and parameters, such as pitch cycle, mean pitch angle, and pitch angle peak, are
TABLE 3  Monthly wind speed statistics

| Wind speed | Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|------------|-------|---|---|---|---|---|---|---|---|---|----|----|----|
| Mean (m/s) |       | 5.27 | 5.04 | 4.80 | 4.47 | 3.99 | 3.42 | 4.73 | 4.33 | 4.51 | 4.95 | 4.98 | 5.53 |
| Standard deviation (m/s) |   | 1.72 | 1.95 | 1.79 | 1.85 | 1.60 | 1.27 | 1.92 | 1.49 | 1.59 | 1.63 | 2.04 | 1.78 |

TABLE 4  Monthly statistics of the pitch behaviour

| Pitch behaviour | Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|----------------|-------|---|---|---|---|---|---|---|---|---|----|----|----|
| Proportion of pitch state time (%) |   | Non-pitch | 82.06 | 84.23 | 85.81 | 87.01 | 92.64 | 94.59 | 80.81 | 92.21 | 89.69 | 84.67 | 82.95 | 78.07 |
| Pitch Increasing pitch | 7.82 | 6.57 | 6.00 | 5.39 | 3.12 | 2.53 | 8.05 | 3.35 | 4.33 | 6.43 | 7.03 | 9.13 |    |
| Decreasing pitch | 8.65 | 7.79 | 6.79 | 6.33 | 3.56 | 2.62 | 9.05 | 3.60 | 4.79 | 7.07 | 8.52 | 10.36 |    |
| Pausing pitch | 1.48 | 1.41 | 1.40 | 1.27 | 0.67 | 0.27 | 2.09 | 0.84 | 1.19 | 1.83 | 1.51 | 2.44 |    |
| Subtotal of pitch state | 17.94 | 15.77 | 14.19 | 12.99 | 7.56 | 5.41 | 19.19 | 7.79 | 10.51 | 15.33 | 17.05 | 21.93 |    |
| Number of pitch cycle | Number of cycles | 5900 | 3963 | 4275 | 3442 | 1582 | 729 | 6350 | 2101 | 2780 | 5453 | 5453 | 3747 | 8553 |
| Mean (s) | 35.11 | 40.71 | 36.98 | 42.67 | 36.28 | 27.34 | 34.33 | 25.40 | 35.55 | 31.34 | 50.78 | 39.17 |    |
| Standard deviation (s) | 55.73 | 78.48 | 66.76 | 75.90 | 77.95 | 46.62 | 50.90 | 34.07 | 55.52 | 46.50 | 92.38 | 61.59 |    |
| Pitch angle peak | Mean (°) | 1.76 | 2.07 | 1.86 | 2.15 | 1.89 | 1.46 | 1.93 | 1.37 | 1.73 | 1.54 | 2.44 | 1.86 |    |
| Standard deviation (°) | 1.95 | 2.87 | 2.41 | 2.61 | 3.06 | 1.89 | 2.22 | 1.51 | 1.86 | 1.57 | 3.04 | 1.91 |    |
| Mean pitch angle | Mean (°) | 1.07 | 1.26 | 1.13 | 1.27 | 1.13 | 0.89 | 1.15 | 0.86 | 1.07 | 0.97 | 1.47 | 1.12 |    |
| Standard deviation (°) | 1.03 | 1.61 | 1.29 | 1.40 | 1.65 | 0.89 | 1.14 | 0.75 | 0.99 | 0.82 | 1.80 | 1.00 |    |

less than 0.5. (4) The correlation coefficients between the standard deviation of wind speed and parameters, including the proportion of pitch time, the number of pitches, the pitch cycle, the mean pitch angle, the pitch angle peak, are all greater than 0.75. It is easy to understand that the proportion of pitch state time and the number of pitch cycles are strongly correlated with both the mean value and the standard deviation of the wind speed. However, no significant correlations are observed between the mean and standard deviation of the wind speed and parameters such as pitch cycle, mean pitch angle, and pitch angle peak.

It can be seen from the above discussion that the proportion of pitch state time and the number of pitch cycles are strongly correlated with the mean value of wind speed, while the number of pitch cycle, mean pitch angle, and pitch angle peak is strongly correlated with the standard deviation of wind speed.

5  |  CONCLUSION

Pitch system is a component system with a high failure rate due to the complex pitch behaviour. In this paper, the pitch behaviour of a large-scale wind turbine is investigated using SCADA data. Four key evaluation indicators describing the pitch behaviour are proposed, that is, the pitch status, pitch

TABLE 5  The correlation coefficient between wind speed and the pitch behaviour

| Correlation coefficient | Proportion of pitch time | Number of pitches | Mean pitch cycle | Mean pitch angle | Mean value of pitch angle peak |
|-------------------------|--------------------------|-------------------|-----------------|-----------------|-------------------------------|
| Mean value of the wind speed | 0.9137 | 0.8729 | 0.4704 | 0.4106 | 0.3790 |
| Standard deviation of the wind speed | 0.7556 | 0.5360 | 0.8273 | 0.8768 | 0.8663 |
time consumption, pitch angle peak, and mean pitch angle. The data pre-processing method for pitch behaviour investigation is studied and the pitch behaviour is investigated based on statistic evaluation. In terms of investigated wind farm conditions and wind turbine, the time proportions for the four states (non-pitch, increasing pitch, pausing pitch, and decreasing pitch) are 85.80%, 5.97%, 1.45%, and 6.78%, respectively. The annual number of pitch cycles is 48,875, and the proportion of pitch state time only accounted for 14.20%. The statistical data trends number of pitch cycles is 48,875, and the proportion of pitch cycles is 85.80%, 5.97%, 1.45%, and 6.78%, respectively. The annual pitch, increasing pitch, pausing pitch, and decreasing pitch) are studied and the pitch behaviour is investigated based on statistic evaluation.

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