XE112-2000 Wind Turbine Yaw Strategy With Adaptive Yaw Speed Using DEL Look-Up Table

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ABSTRACT With the increasing capacity of wind turbines, the importance of the yaw system has gradually become more prominent. The supervisory control and data acquisition (SCADA) system of XEMC Windpower Co., Ltd. is used in this paper to analyze the yaw data of the No. 5 wind turbine of Baozhong Mountain Wind Farm in Hunan Province. In order to evaluate the power generation and the damage equivalent load (DEL) of the yaw bearing during the yaw process, an economic model predictive control (EMPC) yaw strategy based on light detection and ranging (LIDAR) was proposed. EMPC takes the yaw error and wind speed as the disturbance of the cost function (CF) at the same time by establishing the yaw bearing DEL look-up table in advance. Discrete adaptive yaw speed control set is proposed to adapt to different wind conditions sets. Finally, the effectiveness of EMPC is verified using the model of XE112-2000 wind turbine in simulation software Bladed.

INDEX TERMS EMPC yaw controller, minimum cost function, discrete yaw speed finite control set, DEL, Bladed.

I. INTRODUCTION

Yaw misalignment will reduce the wind energy utilization and change the wake flow field [1], at the same time, the blades will be subjected to periodically changing aerodynamic loads, which will aggravate the flapping and vibration of the blades, resulting in changes in the overall performance of the wind turbine, and even damage to the components of the wind turbine [2]. Reference [3] pointed out that the critical value of severe yaw angle that can cause significant loss of wind turbine output power is 10° ~15°, and yaw misalignment will affect the intensity of turbulence at the wake. With the increase of the yaw angle, the maximum value of the wake turbulence increases. Reference [4] found that too fast yaw speed will aggravate the vibration of the nacelle, and at the same time increase the failure rate of the wind turbine. This conclusion demonstrated the importance of the choice of wind turbine yaw speed. Reference [5] studied the influence of yaw misalignments on the load of the main bearing of the turbine, and found that DELs increased with the increase of the yaw error. Reference [6] used a 5 MW horizontal axis wind turbine as the research object, compared the effects of different yaw angles on the wind drive rainfall on the surface of the tower and blades, the additional force of raindrops, and the equivalent pressure coefficient. These studies showed that yaw control is potentially helpful for increasing the power generation and reducing the fatigue load on key parts of the wind turbine. Reference [7] compared proportional integral derivative (PID) control, fuzzy control and MPC control, and then pointed out that logic control still dominates yaw control. In the research of wind turbine yaw controller, more power capture and less use of yaw actuator have always been contradictory issues. Simple threshold control such as Controls Advanced Research Turbine 3-Bladed (CART3) can make the yaw execution more frequent by setting a smaller yaw angle threshold, thereby increasing the power of the wind turbine [8]–[11]. However, the damage load of the key parts of the wind turbine caused by high frequency yaw
execution was not considered. Feedback control can solve this problem, but the delayed response will also bring errors, which will be more obvious in large-capacity MW-class wind turbines [12]. MPC can handle multivariable systems with input and state constraints, by setting different weighting factors to coordinate the effects of different variables [13]. At the same time, MPC can use mature industrial models to predict the future operation of the wind turbine. Therefore, while evaluating the future state, it can also use feedback information to optimize the input [14]. If the disturbance wind is also known through the feedback prediction model, this will further improve the accuracy of the MPC controller [15]. The nacelle-based wind LIDAR can preview the wind speed and direction information in front of the rotor, and has high measurement accuracy [16]–[19], the combination with MPC brought potential room for improvement in wind turbine yaw control. [20] adopted MPC multi-step controller, which can increase the power generation of the wind turbine while maintaining the same yaw utilization rate, and evaluated the performance in different control time horizons. Reference [21] adopted the adaptive wind turbine yaw MPC control method and compared it with the baseline control in the fixed control time horizon. Reference [22] used an ideal upstream wind measurement method, and used a continuously variable yaw speed, and the sub-optimal solution is obtained through secondary programming. Reference [23] proposed a non-linear predictive controller that is different from the conventional structure, and established a discrete predictive model with a larger time step size, thereby greatly reducing the difficulty and time of data processing. Reference [24] proposed MPC yaw control based on a finite yaw speed control set, but the yaw speed is essentially a fixed value.

The EMPC yaw controller in this paper does not need to use a quadratic objective function for optimization like traditional MPC, but adopts a CF directly linked to economic performance [25]. Based on the LIDAR wind measurement, the CF considering the yaw power loss and the equivalent damage of the yaw bearing is proposed. In addition to the yaw error, the wind speed is also included as a disturbance, and the weighting factors are obtained through the Pareto curve in different wind speed ranges. By simulating the yaw process in the wind field, a look-up table of the yaw bearing DEL is included in the CF, then the DEL and power loss are evaluated quantitatively. Discrete adaptive yaw speed subsets are proposed to adapt to different wind conditions, and the sub-optimal solution is obtained through secondary programming. Reference [23] proposed a non-linear predictive controller that is different from the conventional structure, and established a discrete predictive model with a larger time step size, thereby greatly reducing the difficulty and time of data processing. Reference [24] proposed MPC yaw control based on a finite yaw speed control set, but the yaw speed is essentially a fixed value.

The main contributions of this paper are: Using pulse wave LIDAR to preview the wind at three points at the same time to reduce measurement errors. By pre-generating the yaw bearing DEL lookup table, the yaw power loss and the yaw bearing DEL are directly quantified in the CF, which makes the tuning between power and DEL more intuitive. A discrete adaptive yaw speed control set is used to potentially improve the performance of the yaw controller. In addition to the yaw error, the wind speed is also included in the CF, so that the performance of the yaw system under different wind speeds can be fully evaluated.

This paper is organized as follows: Section II describes the composition of the yaw system and analyzes the data of Baozhong Mountain Wind Farm. Section III determines the subsets of the yaw speed control set. Section IV introduces the EMPC yaw controller, including the wind measurement logic of the LIDAR, the composition of the CF and solution method, and then discusses the tuning of the EMPC system. Section V is the simulation results, Section VI is the discussion, and the last section is the conclusion.

### II. OVERVIEW OF WIND TURBINE YAW SYSTEM

As shown in Figure 1, the yaw error angle $\theta_{er}$ is the angle between the nacelle position $\theta_{np}$ and the wind direction $\theta_{wd}$. $\theta_{er} = 0$ when the wind turbine is facing the wind direction. Due to the randomness and fluctuation of wind, the wind direction $\theta_{wd}$ changes continuously, and the yaw error angle $\theta_{er}$ also changes. The yaw system needs to adjust the nacelle position to follow the change of the wind direction until the allowable error range is reached. The power loss caused by yaw misalignment is as follows [26]:

$$P_{loss} = \frac{1}{2} \rho S_{p} C_{p} V_{0}^{3} (1 - \cos^{2}(\theta_{er}))$$ (1)

| TABLE 1. Description of wind farm data collection. |
|-----------------------------------------------|
| **Project** | **Information** |
| Data Sources | SCADA database |
| Wind turbine number | 5f |
| Time | 2021/1/5—2021/1/25 |
| Sampling interval | 10 min |
| Signal channel | wind direction, nacelle position yaw error, turbulence intensity |

![FIGURE 1. Schematic diagram of wind turbine yaw misalignment.](image-url)
where $P_{\text{loss}}$ is the loss power, $\rho$ is the air density, $S_r$ is the sweeping area of blades, $C_p$ is the power coefficient, and $V_0$ is the wind speed. The hardware composition of the yaw system is shown in Figure 2.

As shown in Table 1, we analyzed the data of XE112-2000 wind turbine of the Baozhong Mountain Wind Farm in Hunan Province collected by the SCADA system of XEMC Windpower Co., Ltd., and focused on the yaw status of the No. 5 wind turbine. The location of No. 5 wind turbine is shown in Figure 3. After removing the invalid values from the collected data, the fitting curve is obtained. It can be seen from the statistics in Figure 4 that the proportions of various wind speeds are different, and the proportion of wind speed range between 6m/s and 9m/s is the highest, which is 32%; the wind speed range between 3m/s and 6m/s accounts for 27%; The proportion of wind speed range higher than 12m/s is 11%. Since the pitch control is mainly used when the wind speed is higher than the rated wind speed [25], the wind speed range considered in this paper is 3m/s-12m/s. At the same time, it can be seen that the average yaw error shows a downward trend with the increase of wind speed, which is determined by the characteristics of wind resources: The lower the wind speed, the more frequent the wind direction changes; on the contrary, the higher the wind speed, the weaker the turbulence effect and the more stable the wind direction. Since industrial wind turbines generally do not consider the differences of wind speed characteristics in different wind speed ranges, but adopt the same yaw control logic, the performance of the wind turbine yaw system in different wind speed ranges is quite different [26].

Taylor’s frozen turbulence theory assumes that the turbulence measured upstream reaches the rotor unchanged [28]. The lower the turbulence intensity, the smaller the error when using frozen turbulence theory [29]. As shown in Figure 5, according to the turbulence intensity data collected by SCADA system, we get the curve of turbulence intensity changing with wind speed, and compared with the turbulence intensity provided by IEC standard, we can see that most of the turbulence intensity is below IEC turbulence level C. At this time, the Taylor freezing theory has a smaller error. This
TABLE 2. Ultimate load of the yaw actuator at different yaw speeds.

| Yaw speed / m/s | 0.2°/s | 0.3°/s | 0.4°/s | 0.5°/s |
|-----------------|--------|--------|--------|--------|
| Maximum ultimate load / kN m | 1546.1 | 1546.9 | 1548.6 | 1551.3 |
| Minimum ultimate load / kN m | -118.3 | -119.8 | -123.7 | -127.6 |

TABLE 3. Vibration acceleration of nacelle at different yaw speeds.

| Yaw speed / m/s | 0.2°/s | 0.3°/s | 0.4°/s | 0.5°/s |
|-----------------|--------|--------|--------|--------|
| x-axis acceleration / m/s^-2 | Maximum value | 0.0958 | 0.1067 | 0.1279 | 0.1503 |
| Minimum value | -0.1162 | -0.1173 | -0.1365 | -0.1587 |
| y-axis acceleration / m/s^-2 | Maximum value | 0.0715 | 0.0722 | 0.0821 | 0.0925 |
| Minimum value | -0.0771 | -0.0786 | -0.0851 | -0.0913 |

FIGURE 5. Turbulence intensity statistics.

In the context of the increasing wind turbine capacity, the setting of the yaw speed is particularly important. Too large yaw speed will bring large load and gyroscopic force to yaw actuator, which will affect the life of the yaw system; too small yaw speed will reduce the efficiency of yaw system, prolong the state of yaw misalignment, and increase the fatigue loads of the wind turbine key parts. Since the yaw speed range is typically 0.2°/s-0.8°/s [30], according to the data provided by XEMC Windpower, we test different yaw speeds in the range of 0.2°/s-0.8°/s in a step of 0.1°/s.

According to the simulation results, although the yaw speed range of industrial wind turbine is generally 0.2°/s-0.8°/s, however, when the yaw speed of XEMC Windpower 2MW wind turbine is 0.6°/s, the yaw actuator load begins to appear obvious reverse oscillation. Therefore, the maximum yaw speed subset is set to 0.5°/s; When the yaw speed is 0.2°/s and 0.3°/s, the yaw actuator load oscillation curve, ultimate load and nacelle vibration acceleration are very close, the reduction of the yaw speed has little improvement on the yaw actuator load, so the minimum yaw speed subset is set to 0.3°/s. In summary, the subset of the yaw speed control set is set to 0.3°/s, 0.4°/s, and 0.5°/s.

In the external controller program of Bladed, the judgment of the positive or negative yaw error angle is shown in Figure 1. The direction of the turbine rotor takes the north direction as the 0° reference direction, clockwise is positive, and counterclockwise is negative [31]. Therefore, when the yaw error is positive, the yaw speed uses the control set of Equation (2), and when the yaw error is negative, the wind turbine yaw speed uses the control set of Equation (3).

IV. DESIGN OF EMPC YAW CONTROLLER

A. LIDAR WIND MEASUREMENT MODEL

As shown in Figure 7, a nacelle-based wind LIDAR is located on the top of the nacelle and emits 4 laser beams to the front of the wind turbine. The Doppler effect is used to measure the wind speed and direction at different distances ahead [29]. This paper uses the LIDAR module in Bladed. For the parameter settings of the LIDAR, we refer to the pulse wave nacelle-based wind LIDAR of the Movelsaer Company. As shown in Figure 8, the beam structure is 4 beams, the horizontal plane includes an angle of 30°, the vertical plane includes an angle of 25°, and the measurement frequency is 4 Hz [33].

The time-lapse model of wind is as follows [26]:

$$t_{preview} = \frac{d}{\bar{v}} \quad \text{(4)}$$

where $t_{preview}$ is the preview time of the LIDAR, $d$ is the measurement distance, $\bar{v}$ is the average wind speed, $t_{preview} = mT$, $m$ is the control time horizon of MPC [21]. In this paper, $m$ is chosen as 1.

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The acquisition of the previewed wind direction is closely related to the preview time of the LIDAR. In order to be closer to the real LIDAR measurement distance, we choose the preview time as 30s. Reference [21] discussed three larger preview times and control time horizon, since pulse wave LIDAR can measure wind speed and direction information at different locations at the same time [29], we measure wind at three different distances at the same time, and select the appropriate distance \( d \) according to the 30s average wind speed \( \bar{v}_{30s} \) to deal with different wind speed ranges. When \( \bar{v}_{30s} \) is between 3m/s-6m/s, the measurement distance is 180m; When \( \bar{v}_{30s} \) is between 6m/s-9m/s, the measurement distance is 270m; When \( \bar{v}_{30s} \) is between 9m/s-12m/s, the measurement distance is 360m. The measurement distance \( d \) is selected according to Equation (4), where \( \bar{v} \) selects the maximum wind speed in the three wind speed ranges: 6m/s, 9m/s, 12m/s, so as to ensure the yaw system can act in advance before the wind
Due to the high cost price and installation usually used to evaluate the load loss of important parts of the wind turbine [22]. In the analysis of wind turbine fatigue load, the DEL is considered in this paper. The yaw range considered in this paper is 3m/s-12m/s. Controller will maintain a low sensitivity response [27], so the judgment logic is shown in Figure 9. Since the wind turbine reaches the rotor, and reduce the lag response. The detailed logic is shown in Figure 9. Since the wind turbine uses pitch control as the main control method when the wind speed is higher than the rated wind speed of 12m/s, the yaw controller will maintain a low sensitivity response [27], so the yaw range considered in this paper is 3m/s-12m/s.

### B. DAMAGE RATE OF YAW BEARING UNDER DIFFERENT YAW SPEED SUBSETS

In the analysis of wind turbine fatigue load, the DEL is usually used to evaluate the load loss of important parts of the wind turbine [22]. Due to the high cost price and installation difficulty of the yaw bearing, the life of yaw bearing is generally required to be the same as the wind turbine. Since the main force of the yaw bearing is the overturning moment $M_{xy}$ [32], only the yaw bearing $M_{xy}$ is considered in the DEL of $CF$ in this paper.

We refer to the simulation process of [22], and use the Bladed post-processing module to simulate the yaw bearing equivalent damage rate at different wind speeds and specific yaw angles. This process is repeated at three yaw speed subsets of $0.3^\circ$/s, $0.4^\circ$/s and $0.5^\circ$/s, and the results are shown in Figure 10.

### C. EMPC PREDICTION MODEL AND CF DESIGN

The prediction model of the wind turbine yaw controller is as follows [20]:

$$\theta_{er}(k+1|k) = \theta_{wd}(k+1|k) - \theta_{np}(k) - \dot{\theta}_{np}(k)T_C$$  \hspace{1cm} (5)

where $\theta_{wd}(k+1|k)$ is the wind direction previewed by LIDAR, $\theta_{np}(k+1|k)$ is the predicted nacelle position, $\theta_{np}(k)$ is the current nacelle position, $\dot{\theta}_{np}(k)$ is the current nacelle yaw speed, the value of yaw speed can be $0.3^\circ$/s, $0.4^\circ$/s, $0.5^\circ$/s. $\theta_{er}(k+1|k)$ is the predicted yaw error.

The CF is shown in Equation (6):

$$CF^i = w_{el}E_{loss}(\theta_{er}, V) + w_{bear}D_{bear}(\theta_{er}, V)$$ \hspace{1cm} (6)

In the CF, the power loss of yaw misalignment and the fatigue load of the key components of wind turbine are used as the main parameters of the optimization problem. Where $E_{loss}(\theta_{er}, V)$ is the power loss in the control period, which is obtained by integrating $P_{loss}$ in Equation (1); $D_{bear}(\theta_{er}, V)$ is the damage rate of the yaw bearing during the yaw process, which is obtained through simulation in the Bladed post-processing module in advance, as shown in Figure 7, and is brought into the CF through a two-dimensional lookup table [22]; $w_{el}$ is the weighting factor of power loss, which represents the price of electricity generated; $w_{bear}$ is the weighting factor of the yaw bearing damage load, which is related to the cost price of the yaw bearing. For the solution of CF, we refer to the method in [34] and [11]: different yaw speed subsets $\dot{\theta}_{np}^i (i=0,1,2,3)$ are brought into the prediction model respectively to get the prediction values of yaw error $\theta_{er}^i (i=0,1,2,3)$. Then the yaw error is brought into CF respectively to get $CF^i (i=0,1,2,3)$, compare the size of $CF^i$ and get the minimum CF, so as to get the optimal yaw speed. The specific steps are shown in Figure 11.

Based on [34] and [11], the following improved program code is used to solve the minimum CF. The complete block diagram of EMPC is shown in Figure 12.

Set $CF$ (min) To inf and Set $min$ To inf
For $i = 0: 3$
Use Equation (2),(3),(5),(6) and $V$ to calculate $CF^i$
If $CF^i < CF$ (min) Set $CF$ (min) To $CF^i$ And
Set $min$ To $i$
End
End
Apply $\dot{\theta}_{np}$ (min)
D. EMPC WEIGHTING FACTOR TUNING

For an objective function with two components, the weighting factor can be determined by using Pareto curve based on experience [35], [36]. The selection of the weighting factor $w_{bear}$ refers to the cost price of the yaw bearing of the XE112-2000 2MW wind turbine, which is about $9.8 \times 10^4$ CNY; The selection of $w_{el}$ refers to the price of wind power grid-connected and then makes a selection on this basis. Through preliminary simulation tests, the $w_{bear}$ suitable for different wind speed ranges is selected as $9.93 \times 10^4$. For the selection of $w_{el}$, we need to combine the Pareto curve and its gradient curve at the same time, because a single gradient curve does not show the monotonicity and its specific value [36].

We use the method of [35], taking the generated power $P$ and DEL of yaw bearing as parameters, and use the Pareto curve to find the optimal weighting factor. As shown in Figure 13, as the average power generation increases, the yaw bearing DEL also increases. The smaller the gradient $dL/dP$ of the Pareto curve, the smaller the increase in DEL when the same average power $P$ is increased.

$$\phi_{\text{norm}} = \frac{\Psi_{\text{EMPC}}}{\Psi_{\text{BC}}}$$

In order to compare the EMPC with the baseline control, the average power $P$ and DEL in the curve are normalized by Equation (7), so as to achieve a more intuitive comparison effect, where $\phi_{\text{norm}}$ represents the normalized value, $\Psi_{\text{EMPC}}$ represents the average power generation $P$ and DEL in EMPC, $\Psi_{\text{BC}}$ represents the same parameters under the BC. The BC yaw controller in Bladed uses the average wind direction in the last discrete period as the nacelle position reference of the current control period [22]. In order to simulate the performance of the XE112-2000 2MW wind turbine, the threshold angle is set to $15^\circ$.

The specific steps to obtain the weighting factor are as follows:

1. Change the power loss weighting factor $w_{el}$ from 0.1 to 0.9 with a step size of 0.1.
2. The optimal solution of $CF$ is calculated under different weight factors, and the average generation power $P$ and DEL under the optimal condition are drawn into a Pareto curve, and the gradient curve is calculated.
3. Combined with Pareto curve and its gradient curve, the appropriate $w_{el}$ is obtained under different average wind speed.

In the $CF$, the greater the $w_{el}$, the greater the penalty for yaw power loss, and the yaw power loss will tend to become smaller, that is, the response of the yaw system will be more sensitive. In the high wind speed range, in order to respond to changes in wind direction as soon as possible, we will select a larger power loss weighting factor to make the yaw execution more frequent. In the low wind speed range, more attention is paid to the load of key parts such as the yaw bearing of wind turbine. We will select a smaller power loss weighting factor to reduce the frequency of yaw execution. The duration of the wind speed and wind direction sequence used for calculation is $600$ s, and the average wind speed is $4.5$ m/s, $7.5$ m/s and $10.5$ m/s respectively, to represent three different wind speed ranges.

The corresponding Pareto curve and gradient curve are shown in Figure 14. For the average power $P$ and yaw bearing DEL normalized by Equation (7), we hope that
$P$ is greater than 1, and DEL is less than 1, so that the performance of EMPC is improved compared with BC. In Figure 13a, when $w_{el}$ is 0.5, the gradient is the smallest, and the normalized average power $P$ and yaw bearing DEL also meet the requirements at this time; Similarly, in Figure 13b, when $w_{el}$ is 0.6, both $P$ and DEL are improved and the gradient is relatively small at this time; In Figure 13c, although the corresponding gradient value is the smallest when $w_{el}$ is 0.9, the value of the normalized yaw bearing DEL at this time has exceeded 1, which does not meet our expectations, and it is more appropriate when $w_{el}$ is 0.8. The final power loss weighting factor $w_{el}$ is shown in Table 4.

### Table 4. Objective function coefficient value.

| Wind speed range | 3-6m/s | 6-9m/s | 9-12m/s |
|------------------|--------|--------|---------|
| $w_{el}$         | 0.5    | 0.6    | 0.8     |
| $w_{bear}$       | 9.93x10^4 | 9.93x10^4 | 9.93x10^4 |

### V. SIMULATION RESULTS

We verify the overall performance of EMPC in Bladed, and compare the generation power, nacelle location and the DEL of EMPC yaw controller with BC yaw controller. The wind model uses Kaimal spectrum type, using random turbulence wind seed, turbulence intensity is 3%, and the 3D turbulence...
wind is generated in the Bladed with a time interval of 0.05s. The programming of the external controller is compiled in the form of a dynamic link library (DLL), and all array units are passed in real (floating point) numbers [31], and the communication interval is 0.2s. Figure 15 shows the three wind seeds generated in Bladed. The average wind speeds are 4.5m/s, 7.5 m/s and 10.5 m/s, respectively, corresponding to the wind speed range of 3-6m/s, 6-9m/s, 9-12m/s, the simulation time is 600s.

Figure 16 shows the wind direction and nacelle position at different average wind speeds. It can be seen that under different average wind speeds, the BC yaw controller has basically the same response to wind direction, while EMPC yaw controller exhibits different sensitivity at different average wind speeds. At low wind speed (average wind speed is 4.5 m/s), the EMPC yaw controller is slow to follow the wind direction, and the number of yaw executions is less. In the 600s simulation, the total number is 6, which is the same as that of BC yaw controller; At high wind speed (average wind speed is 10.5 m/s), the EMPC yaw controller is more sensitive to the wind direction, the yaw actuator action is more frequent, there are a total of 9 times in the 600s simulation, which is 6 times more than the BC yaw controller. At medium wind speed (average wind speed is 7.5 m/s), the response of EMPC yaw controller is compromised. The total number of yaw executions is 6 times, which is 3 times more than the BC yaw controller. At the same time, because EMPC uses LIDAR to preview the wind sequence, the yaw action is earlier than the BC yaw controller, and the lag is

![FIGURE 13. Schematic diagram of the Pareto curve obtained by the performance evaluations depending on \( w_{\text{PS}} \).](image1.png)

![FIGURE 14. Pareto curve and its gradient curve under different average wind speeds.](image2.png)

### TABLE 5. Main parameters of XE112-2000 2MW wind turbine.

| Parameters                  | Value |
|-----------------------------|-------|
| Rated power / (MW)          | 2     |
| Rotor diameter/(m)          | 93.2  |
| Sweeping area/(m²)          | 6822  |
| Hub height / (m)            | 78    |
| Blade length / (m)          | 43.6  |
| Cut-in wind speed / (m/s)   | 3     |
| Rated wind speed / (m/s)    | 12    |
| Cut-out wind speed / (m/s)  | 25    |

### TABLE 6. Response time of EMPC yaw controller ahead of BC yaw controller.

| Wind speed | Time point /s | Advance time /s | Average lead time /s |
|------------|---------------|-----------------|----------------------|
| Low        | 30            | 9               | 15                   |
| Medium     | 190           | 22              | 19                   |
| High       | 60            | 13              | 14                   |

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small. As shown in Table 6, when the average wind speed is 4.5 m/s, the yaw response time of EMPC is 15s earlier than that of BC on average; When the average wind speed is 7.5 m/s, EMPC yaw response time is 19s ahead of BC on average; When the average wind speed is 10.5 m/s, the average response time of EMPC is 14s earlier than that of BC yaw controller.

Figure 17 shows the power generation comparison in two control methods. At low wind speed (average wind speed is 4.5 m/s), EMPC power generation increased by 0.2% compared to BC on average; At medium wind speed (average wind speed is 7.5 m/s), EMPC increased by 0.3% compared to BC power generation on average; At high wind speed (average wind speed is 10.5 m/s), EMPC average power generation
is 0.7% higher than BC. In the 1800s simulation of three average wind speeds, the power generation of EMPC is 0.4% higher than that of BC on average, and good performance has been achieved.

Figure 18 is the relative change of the DEL of the EMPC yaw controller to the BC yaw controller, including the yaw bearing, blade, rotating hub, tower bottom and yaw actuator. It should be noted that, except for the load moment of the rotating hub which is the $M_{yz}$, the load moments selected for the other parts are all $M_{xy}$. At low wind speed (average wind speed is 4.5 m/s), the DEL of yaw bearing $M_{xy}$, blade $M_{xy}$, rotating hub $M_{yz}$, tower bottom $M_{xy}$ and yaw actuator $M_{xy}$ decreased by 0.33%, 0.52%, 0.29%, 0.26% and 0.09% respectively compared with the BC yaw controller.
At medium wind speed (average wind speed is 7.5 m/s), compared with the BC yaw controller, the DEL of the yaw actuator $M_{xy}$ of EMPC increased by 0.18%, the DEL of yaw bearing $M_{xy}$, blade $M_{xy}$, rotating hub $M_{yz}$, tower bottom $M_{xy}$, and yaw actuator $M_{xy}$ decreased by 0.22%, 0.45%, 0.29% and 0.21% respectively. At high speed (average wind speed is 10.5 m/s), compared with the BC yaw controller, the DEL of the yaw actuator $M_{xy}$ of the EMPC increased by 0.51%, the DEL of yaw bearing $M_{xy}$, blade $M_{xy}$, rotating hub $M_{yz}$, tower bottom $M_{xy}$, and yaw actuator $M_{xy}$ decreased by 0.16%, 0.32%, 0.28% and 0.13% respectively.

VI. DISCUSSION

In the 1800s simulation, the average power of EMPC is increased by 0.4%, the DEL of the key parts of the wind turbine has also been alleviated. However, the load $M_{xy}$ of
the yaw actuator has increased, which is mainly caused by the more frequent yaw execution in the high wind speed range.

At the same time, it can be clearly seen that since the EMPC yaw controller uses LIDAR to preview the wind sequence, it can respond to changes in wind direction in advance, thereby reducing the lag of the yaw system, which is particularly important in megawatt-class wind turbines. In addition, since the wind speed is also taken into account by the EMPC yaw controller, the power generation is still improved when the number of yaw execution is similar at low and medium wind speeds, especially compared with the traditional BC yaw control which only considers the wind direction change.

For the current control method of XE112-2000 2MW wind turbine of XEMC Windpower, stability is the main goal, but the control method proposed in this paper provides a new design idea for the industrial application of wind turbine yaw system. The discrete adaptive yaw speed control set is a design that is easy to realize, and the speed of the yaw motor can be changed by changing the control logic without changing the hardware of yaw system. This becomes feasible in practical industrial application. It can provide a relatively stable performance improvement without a large amount of calculation. This discrete yaw speed finite control set has also been included in the technical reserve of XEMC Windpower Company. In addition, the $CF$ used by EMPC covers the power loss and the fatigue damage rate of the yaw bearing, which can be directly evaluated as a quantification. This makes the control process of the yaw system of the wind turbine more intuitive. However, the disadvantage is that the amount of engineering required to obtain the equivalent damage rate of the yaw bearing is relatively large, and the complex environmental factors of the wind field such as wake effects are not considered. So there will be a certain deviation from the real operation condition of the wind turbine in the wind farm. In the later research, this problem needs to be further improved to simulate more realistic wind farm conditions.

In addition, the application of LIDAR provides potential improvements for the predictive control of wind turbine yaw systems. Since the LIDAR can preview the wind speed and direction at a long distance in front of the rotor, it can react to the wind direction in advance to reduce the hysteresis of the yaw actuator. Predictive control based on LIDAR does not require complex prediction algorithms to predict wind sequence for a period of time in the future, thereby reducing the dependence on complex prediction models. But at the same time, due to the high dependence of EMPC on the LIDAR preview wind data, the requirements for the accuracy of LIDAR wind measurement are higher. In this paper, the ideal Taylor freezing turbulence theory is adopted in the process of LIDAR wind measurement, and the wind evolution effect in the real wind field is ignored. Although this has been proved feasible in low turbulence wind fields, there is still potential improvement space for the study of wind evolution. At the same time, the LIDAR module in Bladed uses ideal wind measurement, that is, it does not consider the interference of wind turbine blades, which also needs to be optimized and improved in future research.

VII. CONCLUSION
This paper analyzes the wind farm information and wind turbine yaw data of Baozhong mountain Wind Farm in Hunan Province, and EMPC yaw strategy based on LIDAR was proposed in order to evaluate the captured wind energy and the
DEL of the yaw bearing. And the wind speed is also regarded as a disturbance in addition to the wind direction. The tuning of $CF$ in different wind speed ranges is obtained through the Pareto curve. The discrete yaw speed control set suitable for the $\text{XE112-2000}$ $2MW$ wind turbine is selected, and the minimum $CF$ is obtained using the improved solution method. Finally, the simulation in the ideal situation of Bladex shows that the power generation of EMPC yaw controller is $0.2\%$, $0.3\%$, $0.7\%$ higher than that of BC yaw controller in different wind speed ranges, with an average increase of $0.4\%$. In the $1800s$ simulation of three average wind directions, compared with the BC yaw controller, the DEL of the yaw actuator $M_{xy}$ of the EMPC yaw controller increased by $0.21\%$ on average, the DEL of yaw bearing $M_{xz}$, blade $M_{xy}$, rotating hub $M_{yz}$, and tower bottom $M_{xy}$ decreased by $0.23\%$, $0.43\%$, $0.28\%$, and $0.19\%$ respectively on average.

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