

Article

Wind Turbine Load Optimization Control Strategy Based on LIDAR Feed-Forward Control for Primary Frequency Modulation Process with Pitch Angle Reservation

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Abstract: Because wind power is connected to the grid on a large scale, frequency fluctuation in the power grid, which is defined as a system safety risk to the power grid, occurs from time to time. According to the grid code rules of China, wind turbines are required to be equipped with primary frequency modulation or inertia response control capability, which are used to support the safe and stable operation of the power grid. During the traditional frequency modulation process of the wind turbine, power limiting operation or pitch angle reservation is generally adopted to ensure that the reserved energy can be released at any time to support the frequency change in the power grid. However, the frequency support method leads to a large loss of power generation, and does not consider the coordination between mechanical load characteristics control and primary frequency modulation. In this paper, a mechanical load optimization control strategy for a wind turbine during the primary frequency modulation process, based on LIDAR (light detection and ranging) feed forward control technology, is proposed and verified. Through LIDAR feed forward control, the characteristics of incoming wind speed can be sensed in advance, with the consequence that the wind turbine can participate in, and actively control, the primary frequency modulation procedure. According to the characteristics of incoming wind, for instance the amplitude and turbulence, simultaneously, the size of the reserved pitch angle can be adjusted in real time. This kind of method, coordinating with the mechanical load of the wind turbine, can be used to reduce both the ultimate load and fatigue damage as much as possible. Finally, the mechanical load characteristics of the wind turbine with and without the control strategy are compared and studied through simulation. The research results show that the load optimization control strategy based on LIDAR feed-forward control technology can effectively reduce the fatigue and ultimate loads of the wind turbine while supporting the frequency change in the power grid; especially for the fatigue load of tower base tilt and roll bending moments, the reducing proportion will be about 4.3% and 6.3%, respectively.



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1. Introduction

As the capacity of grid-connected wind power continues to rise, the proportion of wind power in local areas of China has exceeded more than 70%. Due to the inherent characteristics of the wind turbine, the high proportion of wind power systems have a low disturbance rejection, weak inertia and frequency/voltage support characteristics. Grid code faults, such as voltage falls, frequency fluctuation and other kinds of grid disturbances, occur frequently. Especially against the background of the renewable energy development of “carbon emissions peak and neutrality”, the penetration rate of wind power is getting higher and higher; meanwhile, the equivalent inertia of the power system is constantly decreasing in China, added to which the probability of grid disturbances becomes greater.

The frequency modulation capability of thermal power units can no longer fully meet the requirements of the power grid to maintain the stability of frequency. Renewable energies, such as wind power, are required to have frequency response characteristics and frequency modulation control capabilities, which are similar to traditional thermal power units.

However, in order to pursue the best utilization efficiency of wind energy, the generator speed and grid frequency are completely decoupled, which makes it difficult for the wind turbine to make a timely response to the fluctuation in the grid frequency. In the case of wind turbines, therefore, they are required to support and meet corresponding requirements of the grid code, while frequency disturbance happens, and ensure that it has a similar primary frequency control ability to a conventional generator. When the grid frequency drop occurs, due to a load surge or power network disconnection, the wind turbine is needed to rapidly increase the active power output, supply a persistent energy input to the power grid, and to support and lift the power grid frequency [1]. On the contrary, while the grid frequency is raised, the wind turbine is needed to rapidly reduce the active power output to drag down the grid frequency. Figure 1 below shows a typical grid frequency disturbance process.

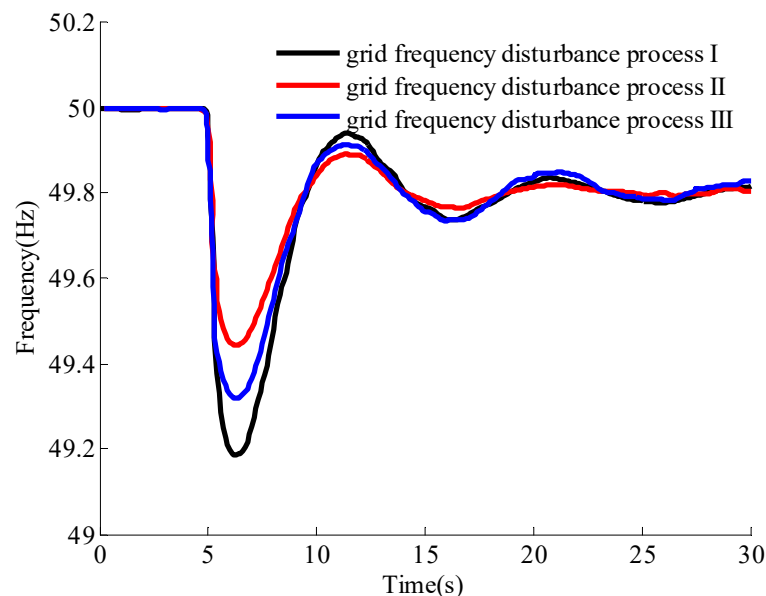


Figure 1. Different frequency disturbance processes of the power grid.

In order to ensure the frequency stability of the power grid, wind power, as an important part of the power grid, is required to have the ability of frequency regulation, similar to conventional power sources, such as rotating reserve, inertia response and primary frequency modulation. Currently, power grid code guidelines issued by different countries and regions with high wind power penetration have clearly required grid-connected wind farms to provide an auxiliary frequency modulation function. Accordingly, for wind turbines in wind farms, corresponding requirements have been proposed regarding the frequency modulation control capability [2].

As shown in Figure 2, during the process of grid frequency disturbance, when the amplitude of the power grid frequency fluctuation is within 0.1 Hz, the wind turbine does not start the frequency modulation control strategy. However, when the grid frequency falls between 49.8 Hz and 49.9 Hz, the wind turbine is required to support a certain proportion of additional active power, which is also according to the fluctuation range of the grid frequency. Especially, while the power grid frequency drops continuously and is lower than 49.8 Hz, the wind turbine is required to release more active power, which is up to 10% of the rated power, to support the stable operation of the power grid. Conversely, during the power grid frequency lifting process, the wind turbine is required to reduce its output,

maybe only by increasing the blade angle to lower the power grid frequency. Generally, the control process of reducing the active power output of the wind turbine is relatively common and traditional.

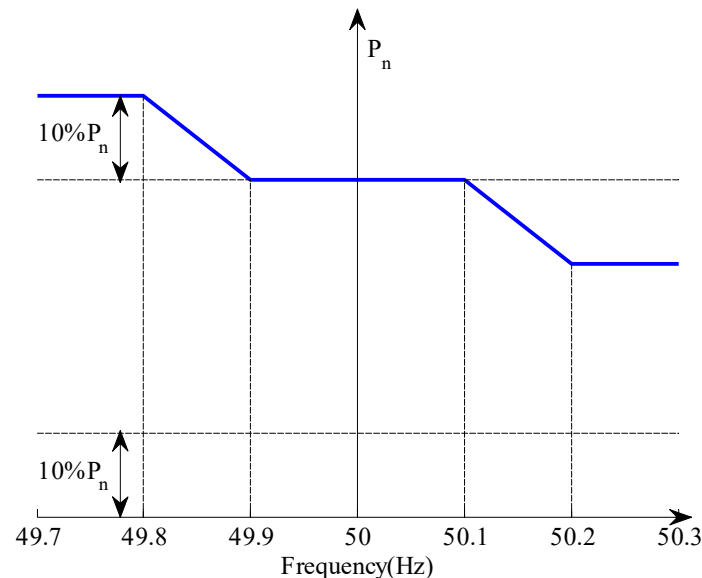


Figure 2. Wind turbine frequency support requirements of China [3].

Recently, there has been some research which has focused on the frequency modulation control of wind turbines. In order to improve the power quality and maintain the stable output generated from wind turbines, configured with a squirrel-cage induction generator, Minh Quan Duong et al. presented a hybrid controller based on PI (proportion integration) and a fuzzy technique for the pitch angle controller, which has been one of the most common methods for smoothing output power fluctuations. With this method, the power quality of wind turbines is significantly improved to ensure the stability and reliability of the power system [4]. Yan Xiangwu et al. combined the control characteristics of the grid-side converter of the doubly fed wind turbine, and proposed an adaptive control strategy for the inertia and primary frequency modulation of the doubly fed induction generator (DFIG) based on the state-of-charge (SOC) control of super-capacitor energy storage, which can automatically adjust the frequency modulation control [5]. Following the control strategy of frequency regulation of the DFIG, Yan Gangui et al. obtained a deloading operation control strategy, which was coordinated with the speed and pitch control. The simulation results show that the operation curve can deploy the frequency regulation capacity effectively and improve the rationality of frequency dispatch [6]. Lan Fei et al. proposed a frequency regulation strategy of the wind turbine based on a deloading power tracking curve and gave a detailed analysis of the specific process of the deloading control in each wind speed area. Simulation results show that the proposed frequency modulation control strategy can improve the frequency stability of the power system [7]. Hu Jiaxin et al. proposed a strategy of frequency control for a deloaded wind turbine generator based on coordination between the rotor speed and pitch angle. Different strategies are applied according to the deloading level. A parameter optimization module and frequency control module are added into the wind turbine generator control system to implement frequency control. The related simulation results illustrate that the proposed control method has a better frequency regulation performance than conventional methods [8]. In order to explore the frequency modulation potential of doubly fed wind turbines, Zhang Zhaosui et al. proposed a frequency modulation control strategy, coordinated with overspeed and variable pitching. According to different wind speed conditions, frequency modulation is divided into three modes, and the criteria for identifying these three modes are analyzed in

detail. The simulation results show that this control method can effectively improve the frequency stability of the power system [9].

This literature proposed a series of practical methods for the strategy and implementation of wind turbine frequency modulation control [10–15], and additionally verified them from the perspective of simulation. However, there is an important point, which is that they did not consider the coordination and linkage between the realization of the frequency modulation function of wind turbines and the mechanical load control. Especially for the wind turbines, which possibly switch frequently between a normal power generation mode and a frequency modulation mode for a long time period, the power generation loss and fatigue load damage of the mechanical system structure are typical, but usually ignored. This paper is focused on the discussion and analysis of wind turbine mechanical load optimization control during the frequency modulation process with LIDAR feed-forward technology.

Based on the frequency modulation strategy of the pitch angle standby mode in a typical grid frequency disturbance process, this paper is focused on how to realize a coordination between the frequency modulation function and mechanical load control of the main components of the wind turbine. A mechanical load optimization control strategy for the wind turbine during the primary frequency modulation process, based on a LIDAR feed forward control, is proposed. The state-of-the-art LIDAR is used to accurately predict and perceive the incoming flow characteristics of the wind turbine; in combination with the perceived incoming flow characteristics, the wind turbine can adjust the pitch angle of blades in advance to respond to the power grid frequency fluctuation. While realizing the frequency modulation control of the wind turbine, it may help to reduce the power loss caused by an excessive pitch angle reservation, and optimize the mechanical load control, meanwhile reducing the ultimate and fatigue load of the main structural components of the wind turbine.

2. Wind Turbine Primary Frequency Modulation and Basic Control

At present, according to different energy forms and sources, the methods for wind turbines to participate in primary frequency modulation mainly include three solutions, namely rotor kinetic energy control, power reserve control, and wind storage combined control. Among the three, the power reserve mode can be summarized as a variable pitch angle and over speed control mode [16]. The frequency modulation control of wind turbines using a variable pitch angle control is to control the active power output of wind turbines by increasing the pitch angle of blades, with the result that the active power output is normally lower than the power output in the maximum power output tracking operation mode; the difference is hence used to support the adjustment process of the power grid frequency. Basing their research on the traditional time-delay signal elimination phase-locking principle, Wang Jisong et al. proposed a specific time-delay signal elimination phase-locking method which considers system frequency changes. Given the premise that wind turbines have spare power, the virtual inertia and pitch control are combined to realize the primary frequency modulation function of wind turbines [17]. Some scholars have additionally designed intelligent algorithms to predict the change in the wind speed by means of machine learning, and adjusted the design of the frequency modulation strategy based on the change in wind speed [18–23]. The active power output of typical wind turbines can be expressed as:

$$P(v_i) = 0.5\rho A v_i^3 C_p(\lambda, \beta) \quad (1)$$

$$C_p(\lambda, \beta) = (0.44 - 0.0167\beta) \sin\left(\frac{\pi(\lambda - 3)}{15 - 0.3\beta}\right) - 0.0018(\lambda - 3)\beta \quad (2)$$

$$\lambda = \frac{\omega R}{v_i} \quad (3)$$

where ρ —air density, kg/m^3 ; A —rotor swept area, m^2 ; v_i —the average wind speed, m/s ; $C_p(\lambda, \beta)$ —the power coefficient; λ —blade tip speed ratio; β —blade pitch angle, rad ; R —wind turbine rotor radius, m ; ω —rotor speed, rad/s .

The blade pitch angle of the wind turbine is a key variable of the power coefficient. The power coefficient curves of the wind turbine under different pitch angle settings are shown in Figure 3 below.

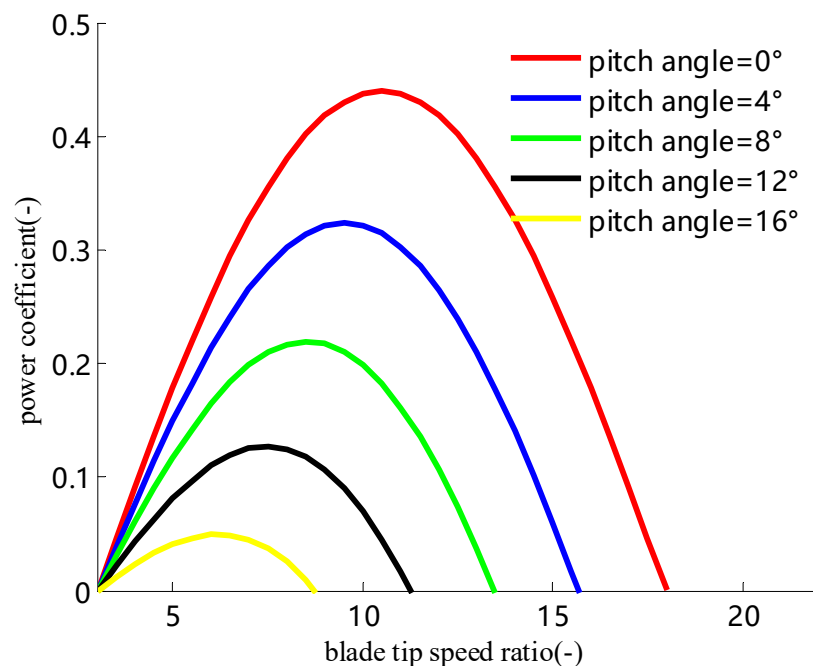


Figure 3. Relationship between blade tip speed ratio and power coefficient at different pitch angles.

Under the conditions of the same tip speed ratio, the larger the blade pitch angle, the smaller will be the active power output, which means larger standby power capacity. Control of the pitch angle change can realize power regulation with different wind conditions, but the obvious disadvantage is that the variable pitch actuator is a mechanical structure, which requires more response time. Additionally, frequent pitch angle changes will also accelerate the mechanical wear and increase the maintenance costs of the pitching actuator system. The basic method of wind turbine frequency modulation control based on a pitch angle reservation is shown in Figure 4 as below.

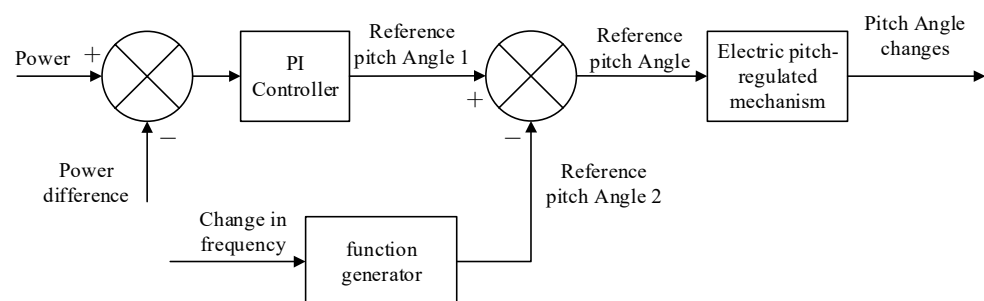


Figure 4. Basic method of frequency modulation based on pitch angle reservation.

In most working conditions, the control of the pitch angle change can effect a load reduction in the wind turbine, and this control strategy can participate in a power system frequency adjustment. Based on a 3 MW doubly fed wind turbine, this paper simulates and calculates the output characteristics of the wind turbine under different initial pitch

angle settings. The basic parameters of wind turbine simulation are shown in Table 1 below, while the power curve simulation results are shown in Figure 5 below.

Table 1. Wind turbine main parameters.

Parameter	Value	Parameter	Value
Wind turbine type	Double-fed	Design class	S
Rotor speed/r.min ^{−1}	11	Rotor diameter/m	140
Rated wind speed/m.s ^{−1}	9.1	Hub height/m	100
Cut in wind speed/m.s ^{−1}	3	Rated power/kW	3000
Cut out wind speed/m.s ^{−1}	20	Rated voltage/kV	0.69

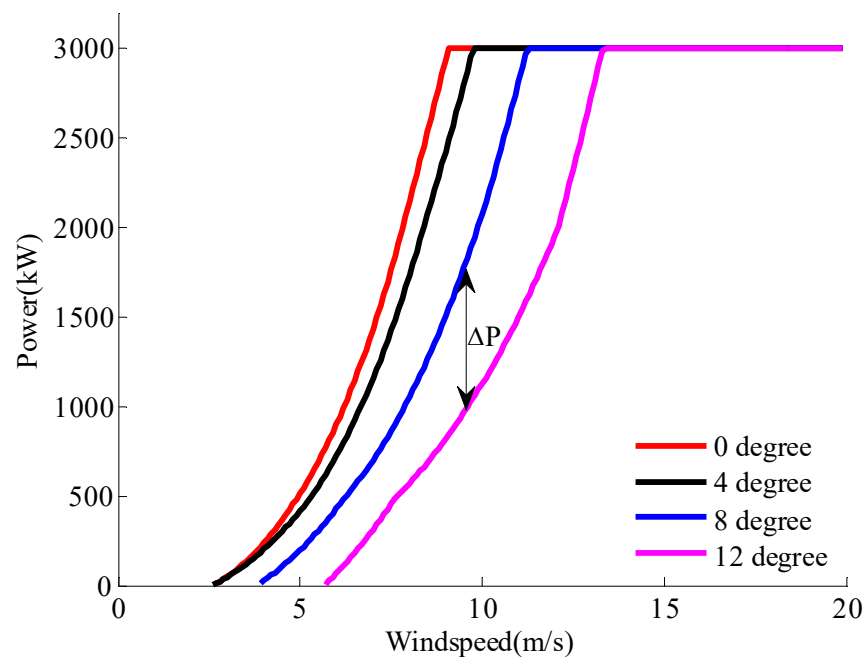


Figure 5. Wind turbine power curves at different pitch angles.

At a certain wind speed v_i , when the blade pitch angle of the wind turbine β_a increases to β_b , the power coefficient of the wind turbine changes from $C_p(\lambda_a, \beta_a)$ to $C_p(\lambda_b, \beta_b)$, thus generating different active power outputs. It can be expressed as:

$$\Delta P(v_i) = 0.5\rho A v_i^3 (C_p(\lambda_a, \beta_a) - C_p(\lambda_b, \beta_b)) \quad (4)$$

The control of the pitch angle change reduces the output of the wind turbine by changing the blade pitch angle to achieve a certain reserve capacity.

Table 2 below shows the active power reserve situation of the 3 MW double-fed wind turbine with different pitch angle setting modes and wind speed ranges.

It can be summarized from Table 2 that at different wind speed intervals, effective power reservation can be realized by adjusting the pitch angle of wind turbine blades. Theoretically, for this type of wind turbine, when the wind speed is 9 m/s, the wind turbine can reserve 1825 kW, in other words about 60.8% of the rated power for backup (the blade pitch angle is adjusted to 10°) through the pitch angle change.

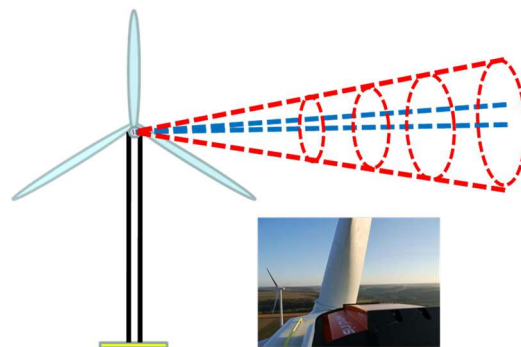
Table 2. Reserved power capacity at different pitch angles.

Wind Speed/m·s ⁻¹	Power Reserve Capacity at Different Reserved Pitch Angles/kW				
	2°	4°	6°	8°	10°
5.0	30.6	96.7	193.3	317.0	463.6
5.5	41.4	134.8	248.8	383.1	541.5
6.0	53.7	175.0	322.4	469.7	639.1
6.5	68.3	222.5	410.0	587.3	759.8
7.0	85.3	277.9	512.0	733.6	916.5
7.5	105.0	341.8	629.8	902.3	1127.3
8.0	124.0	410.5	759.9	1090.7	1363.7
8.5	156.5	460.5	873.9	1270.5	1598.1
9.0	179.3	517.5	965.7	1436.6	1825.4
9.5	0.0	204.6	682.7	1230.0	1687.4
10.0	0.0	0.0	318.5	926.1	1466.9
10.5	0.0	0.0	0.0	567.0	1223.3
11.0	0.0	0.0	0.0	184.1	943.8
11.5	0.0	0.0	0.0	0.0	565.7
12.0	0.0	0.0	0.0	0.0	170.8

3. Primary Frequency Modulation and Load Control Strategy Based on LIDAR Feed-Forward Control

3.1. LIDAR Feed-Forward Control

In recent years, with the rapid development in advanced sensing and internet of things technology (IoT), many scholars have carried out research on the optimization of wind turbine control characteristics based on smart sensing equipment and algorithm technology. Wind turbine feed-forward control, based on the nacelle-based LIDAR, is a popular research direction. LIDAR is a state-of-the-art wind characteristic measurement device based on the principle of the optical Doppler, ignoring the instantaneous time delay characteristics of light waves; LIDAR can measure wind speed and direction at different locations and levels at the same time. In particular, the nacelle-based LIDAR, which is installed on the top of a wind turbine nacelle, uses the forward laser beam emitted by itself to realize the advance perception of the incoming flow characteristics (wind speed and direction) of the wind turbine. With the incoming information on the wind flow, the control process of the wind turbine will be changed from passive control to active control. Figure 6 shows the basic operating principle of LIDAR.

**Figure 6.** Operating principle of LIDAR.

Han Bing et al. proposed a LIDAR-assisted wind turbine model predictive control method to realize the feed-forward compensation control of the control system, which is aimed at adjusting the wind speed disturbance [24]. In fact, the wind condition of the wind farm is usually complex and changeable, and the pitch control of the traditional wind turbine is lagged and easily leads to an over-pitch change, which will increase the plane thrust and frequent pitch change of the wind turbine; this will affect the fatigue load of

the blade root as well as the tower base. The LIDAR feed-forward control can accurately measure the wind speed in real time, which can also effectively solve the problem of the lag in the traditional wind turbine variable rotor control, and reduce the ultimate and fatigue load of the key components of wind turbine.

Without consideration of the feedback time of the laser optical path, it can be approximated that the nacelle-based LIDAR can measure the wind speed and direction information at different sections in the incoming flow direction in real time. Wind speed characteristics in the forward wind speed flow field of the rotor can be measured by the nacelle-based LIDAR, as shown in Figure 7. Considering the time-varying characteristics of the wind speed, the wind speed measured by the nacelle LIDAR cannot be directly applied to the subsequent feed-forward control of wind turbines. In this paper, the wind speed used to participate in the feed-forward control is not the wind speed directly measured by a certain wind speed measurement section, but the wind speed of each section of the wind flow, considering the comprehensive calculation of the horizontal wind shear coefficient, distribution characteristics and LIDAR advance prediction time.

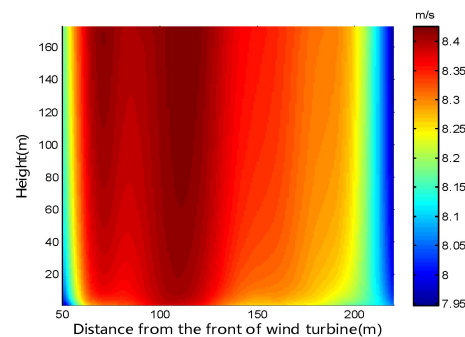


Figure 7. Wind speed distribution in front of the nacelle.

Based on the feed-forward control algorithm of the nacelle-based LIDAR, it mainly measures the wind speed in the direction of the incoming flow by reasonably setting the LIDAR signal advance prediction time and low-pass filter parameters, and calculates the wind speed and wind direction changes in the center of the hub in advance through a frequency domain analysis and Kalman filtering method. The feed-forward control algorithm is designed, and combined with a conventional pitch control, and the pitch command is then given in advance. The prechange in the pitch angle not only ensures the stability of the speed control, but also reduces the change in the wind turbine plane thrust, thereby reducing the fatigue load at the blade root and tower bottom. The basic strategy logic of feed-forward control of the wind turbine based on the nacelle-based LIDAR is shown in Figure 8 below.

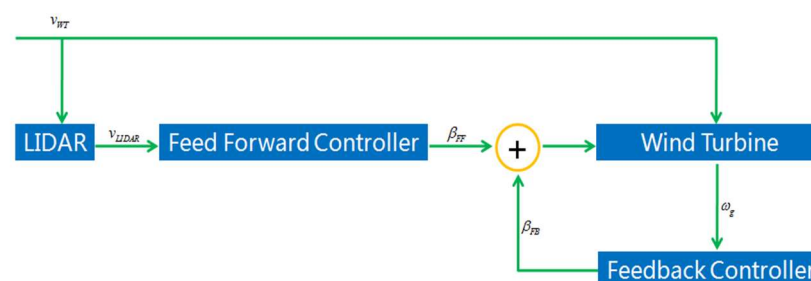


Figure 8. LIDAR feed-forward control strategy.

By measuring the wind speed of the remote incoming flow, we can estimate the appropriate blade pitch angle and compare it with the pitch angle at the current moment.

The variable blade angle of the wind turbine is adjusted in advance, and the variable blade speed can be set as follows:

$$\dot{\beta}_{FF}(t) = \frac{\beta(v(t+\tau)) - \beta(v(t))}{\tau} \quad (5)$$

$$\tau = \frac{F \cos(\alpha)}{v_c} \quad (6)$$

where $\dot{\beta}_{FF}$ is the pitch rate; $\beta(v(t))$ is the pitch angle when the wind speed is $v(t)$; $\beta(v(t+\tau))$ is the pitch angle when the wind speed is $v(t+\tau)$; τ is the look-ahead time; F is the focal length; α is the half-cone angle of the LIDAR; v_c is the airflow velocity.

It should be emphasized that the wind speed measured by the nacelle-based LIDAR is the wind speed at the measurement location of each beam. Only the wind speed component along the beam is measured, and other components need to be assumed. In addition, the LIDAR does not sample the entire scanning area. Furthermore, it is necessary to estimate the equivalent wind speed of the rotor from the wind speed obtained from each beam of the laser; that is, the wind speed needs to be converted into the rotor averaged wind speed (RAWS) of the rotor plane. Considering that the high-frequency part of the measured turbulence will change when it reaches the center of the rotor, a second-order low-pass filter with a cut-off frequency of 3 rad/s and a damping ratio of one is used to filter the RAWS to remove the non-uniformity caused by the sampling frequency continuity.

3.2. Primary Frequency Modulation and Load Control Strategy Based on LIDAR Feed-Forward Control

The basic hypothesis of the research in this paper is that the wind turbine adopts the pitch angle standby mode for primary frequency modulation during the process of the grid frequency drop. The frequency modulation control scheme is conservative. Although it can participate in the frequency modulation and actively support the power grid, it loses power generation and cannot predict the incoming wind conditions to achieve active control of the wind turbine and reduce the typical load of the main components. In this paper, combined with the nacelle LIDAR feed-forward control strategy, according to the wind speed sensed by LIDAR and the actual demand of the current reserved pitch angle, the pitch angle of the wind turbine blades is dynamically adjusted in real time to ensure a certain amount of active power reserve to support the grid frequency change. At the same time, it reduces the loss in power generation and reduces the fatigue load of the wind turbine. The logic of the primary frequency modulation control strategy based on the LIDAR feed-forward control is shown in Figure 9 below.

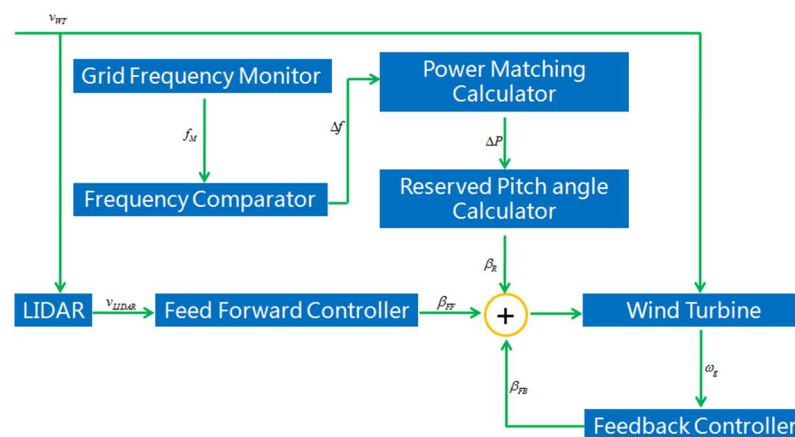


Figure 9. Primary frequency modulation control strategy based on LIDAR feed-forward.

Based on the primary frequency modulation control strategy of the LIDAR feed-forward control, the grid frequency monitor and the corresponding reserved pitch feedback calculation module are introduced on the basis of the LIDAR feed-forward control strategy. The grid frequency monitor monitors the power grid frequency in real time. The monitored frequency f_M is compared with the set frequency of the power grid, 50 Hz, and the frequency deviation Δf is calculated. According to the related demand of the wind turbine frequency modulation as shown in Figure 2, the active power ΔP , which needs to be supported by the wind turbine under the current state, is calculated. Based on the active power support deficiency required by the primary frequency modulation process, the variable pitch angle β_R of the wind turbine under the current wind speed is calculated by the wind turbine controller.

4. Primary Frequency Modulation and Load Characteristics Simulation Based on LIDAR Feed-Forward Control

On the basis of a 3 MW doubly fed wind turbine model, this paper simulates the primary frequency modulation and mechanical load characteristics of the wind turbine based on LIDAR feed-forward control, focusing on the mechanical load characteristics of the wind turbine's key components. Firstly, the turbulent wind with an average wind speed of 12 m/s is used as the input condition to simulate the load characteristics with and without the LIDAR feed-forward controller mode, which is used to compare and verify the load characteristics of the main components of the wind turbine. Figures 10–12 show the transient load response characteristics of the mechanical components of the wind turbine, with and without the LIDAR feed-forward controller. We can see that there is a significant drop in the tower base bending moments, compared to the case without the LIDAR, which can be summarized as Table 3.

Table 3. Tower base bending moment comparison with/without LIDAR control.

Parameter	With LIDAR	Without LIDAR	Rate
Tower base M_x maximum	3.39×10^3 kNm	3.60×10^3 kNm	94.41%
Tower base M_x amplitude	2.54×10^3 kNm	2.87×10^3 kNm	88.51%
Tower base M_y maximum	4.31×10^4 kNm	4.41×10^4 kNm	97.90%
Tower base M_y amplitude	1.33×10^4 kNm	1.46×10^4 kNm	91.21%

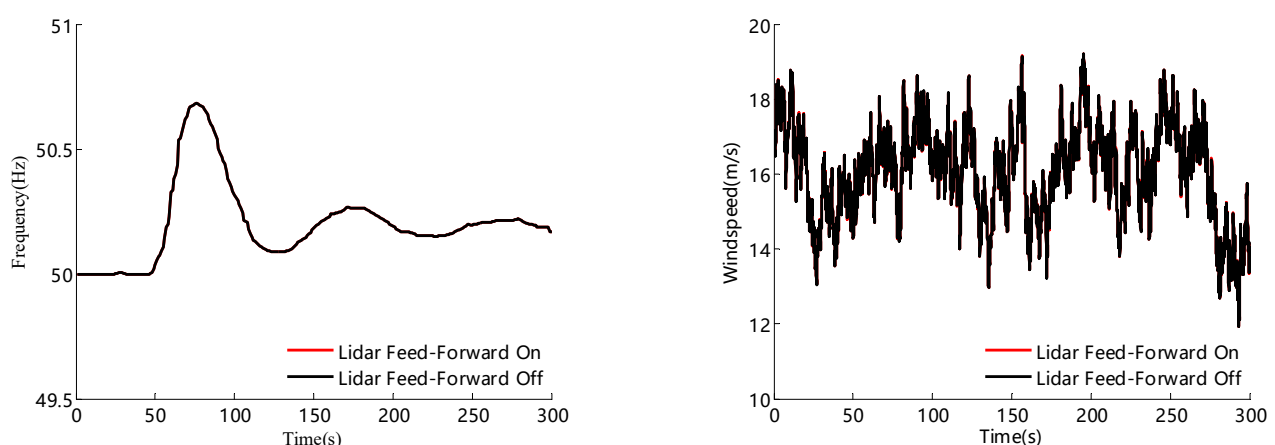


Figure 10. Grid frequency and wind speed time series (input of simulation).

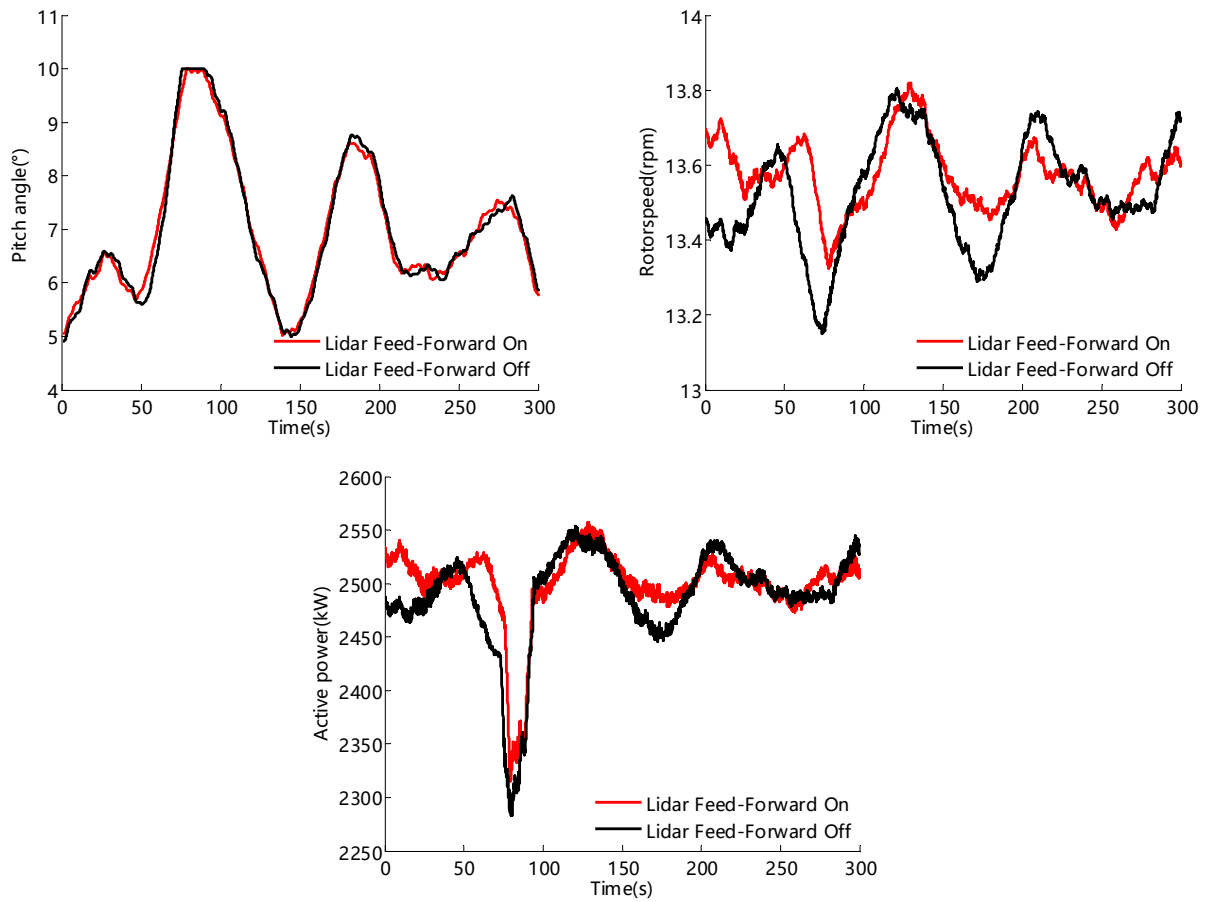


Figure 11. Pitch angle, rotor speed and active power comparison.

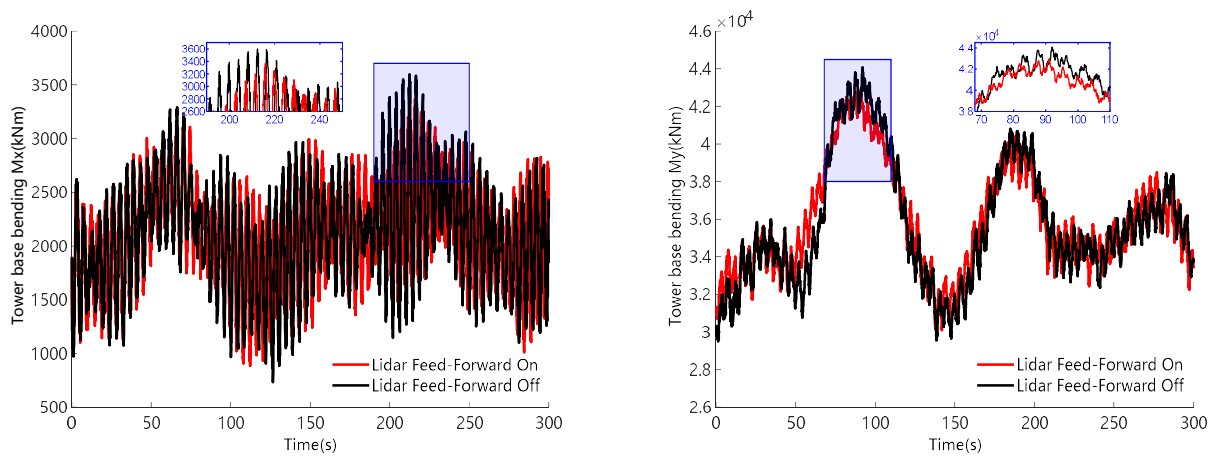


Figure 12. Tower base M_x and M_y bending moment time series comparison.

In order to further explore the difference in the influence of fatigue load characteristics of the wind turbine structural components with and without the LIDAR feed-forward controller, the fatigue equivalent load characteristics are also analyzed and studied in this paper. The fatigue equivalent load is defined as follows:

$$R_{eq} = \left(\frac{\sum R_i^m \times n_i}{n_{eq}} \right)^{m^{-1}} \quad (7)$$

where R_{eq} —fatigue equivalent load, kNm; n_i —number of cycles of rainflow counting; R_i —amplitude of cycles of rainflow counting, kNm; n_{eq} —designed number of cycles; m —parameter of material characteristics (slope of material S-N curve).

The comparison of the fatigue equivalent load of the tower bottom bending moments, with and without the LIDAR feed-forward controller during the primary frequency modulation process is shown in Figures 13 and 14 below.

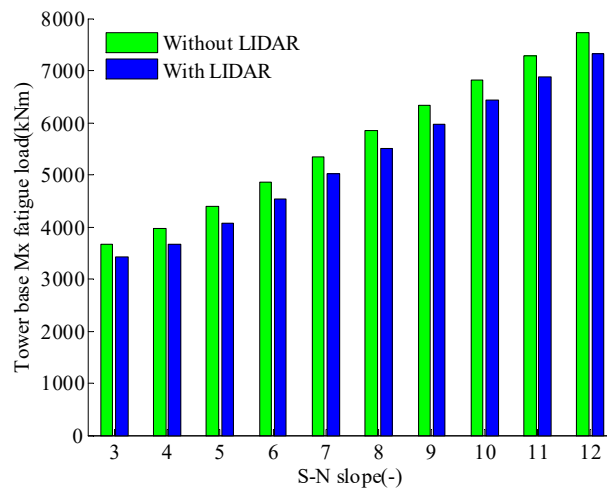


Figure 13. Tower base Mx bending moment fatigue equivalent load comparison (with and without LIDAR feed-forward control).

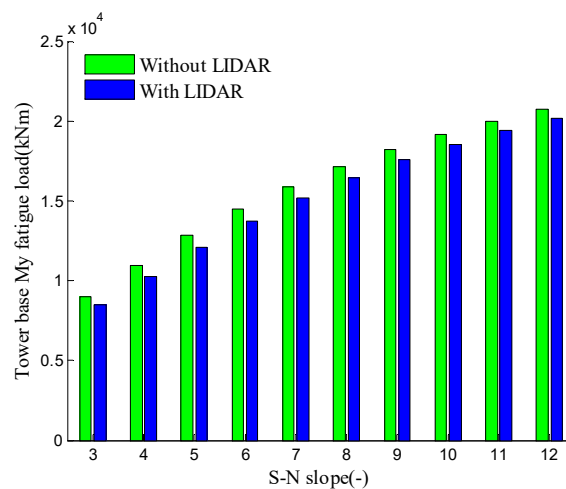


Figure 14. Tower base My bending moment fatigue equivalent load comparison (with and without LIDAR feed-forward control).

The simulation results show that the use of the LIDAR feed-forward controller has a significant effect on reducing the fatigue load of the main components of the wind turbine, especially for the critical loads on the tower bottom bending moments of the wind turbine. Statistically, the fatigue load of the tower base Mx bending moment was reduced by an average of 6.3%, while the fatigue load of the tower base My bending moment was reduced by an average of 4.3% approximately.

5. Conclusions

In this paper, firstly, the frequency modulation control strategy and implementation process of the wind turbine based on a pitch angle reservation was described and analyzed. Based on a 3 MW doubly fed wind turbine, the active power reserve of the frequency

modulation process based on a pitch angle reservation was simulated and analyzed. Considering that the existing frequency modulation control strategy based on a pitch angle reservation ignores the power output loss of the wind turbine and the load characteristics of the mechanical system of the wind turbine, a load optimization control strategy for the frequency modulation process of the wind turbine based on a LIDAR feed forward control is proposed; this may significantly optimize the existing frequency modulation control strategy, while achieving the support of the grid frequency, as well as reducing the ultimate and fatigue load of the mechanical components of the wind turbine. Especially considering the case that, during the whole design operation life of the wind turbine, normally 20 years, the mechanical load optimization control strategy, proposed in this paper, can also help to reduce the cumulative fatigue damage to the wind turbine and its maintenance costs.

Author Contributions: Conceptualization, D.F.; methodology, D.F.; software, L.K.; validation, L.G.; formal analysis, D.F.; investigation, A.W.; resources, H.J.; data curation, L.K.; writing—original draft preparation, D.F.; writing—review and editing, L.K.; supervision, N.Z. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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