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Research on Joint Power and Loads Control for Large Scale Directly Driven Wind Turbines

Emphasis of this article is on the dynamic characteristics analysis of individual pitch control for MW scale directly driven wind turbines with permanent magnet synchronous generator (PMSG). The pitch control objectives were analyzed and the objective expressions were deduced, including power expression, loads expression, and vibration expressions of blade and tower. Then, both the collective pitch control aiming at power control and the individual pitch control strategy aiming at joint power and loads control were analyzed, too. The blade root bending moments and the actual capture power of wind rotor were employed to be the control variables. The power was calculated based on the conventional measured parameters of wind turbines. In order to reflect the difference between the pitch angle command value and the actual value, the pitch actuator dynamic model was used. The research results show that both the collective pitch control strategy and the proposed individual pitch control strategy can effectively control the power injected into grid; moreover, the individual pitch control can reduce fatigue loads; while in the process of individual pitch control, the actual variation of blade pitch angle is closely related to not only the inflow speed but also the blade azimuth angle; individual pitch control strategy can reduce the variation amplitude of flapwise moments, but has little influence on the edgewise moments. [DOI: 10.1115/1.4025707]

Keywords: directly driven wind turbines, pitch control objective, individual pitch control, fatigue loads

1 Introduction

Nowadays, the collective pitch control strategy has been widely used in modern large scale wind turbines. Recently, much attention has been paid by many researchers to the individual pitch control strategy. However, whether the collective pitch control or the individual pitch control is adopted it is the main trend in development that each blade has individual pitch drive mechanism in modern large scale wind turbines. Then, it is possible to abolish the large and expensive brake system of wind turbines and to employ individual pitch control strategy for each blade. Especially, modern large scale wind turbines have rotor diameters in excess of 100 m. During the process of rotor rotation, blade loads have different values at different azimuth angles and the loads difference is significant. Meanwhile, some other loads, including the bearing loads, main shaft loads, and tower loads fluctuate accordingly. Nevertheless, the widely used collective pitch control strategy concerns only wind power capture and cannot reduce the fatigue loads. Many researchers attempt to employ the individual pitch control strategy to reduce fatigue loads. In order to reduce the loads, the PI controller or linear-quadratic-Gaussian (LQG) controller design methods are employed to calculate several control actions from several measured signals [1,2]; these are the earlier introductions on the individual pitch control. The H∞-norm minimization approach is employed to design decoupled controllers for collective and cyclic pitch based on the simplified model for coupled axial structural dynamics of tower and blades in Ref. [3]. A control approach is presented to reduce fatigue loads, which has a two-degree-of-freedom structure, consisting of an optimal multivariable LQG controller and a feed-forward disturbance rejection controller based on estimated wind speed signals in Ref. [4]. A load-reducing control strategy using individual blade control is presented based on local blade inflow measurements in Ref. [5]. An individual pitch controller is designed to reduce power fluctuations, platform rolling rate, and platform pitching rate of the floating wind turbines in Ref. [6]. An individual pitch control strategy is presented which combines fuzzy control with weight number in Ref. [7]. The field test on the hundred thousand watt scale wind turbines (CART2 and CART3) shows that the individual pitch control is feasible [8–10]; it provides a useful reference for further implementation on MW scale and other types of wind turbines.

Despite that the research on individual pitch control has been pushed forward by employing different control strategies and means from different angles, many issues need to be studied in depth. For example, many individual pitch control strategies are based on state equation of wind turbines which is difficult to obtain because wind turbines system is a complex nonlinear system involving in multiphysics field and multiphysics processes; in many articles, the tilt and yaw moments are selected to be the feedback signals which are difficult to be directly measured and calculated based on the blade root bending moments by virtue of the linear model of wind turbines; when analyzing the pitch control characteristics, the pitch actuator is usually denoted by a first order lag, a second order response, or even higher order transfer function, but the more detailed model is needed for detailed calculations. In this paper, the selected feedback signals are the blade root bending moments; the linear model and state equation of wind turbines are not involved, and the pitch actuator dynamic model is used.

In Sec. 2, directly driven wind turbines with PMSG are studied wind turbines. First, the pitch control objectives are analyzed and the objective expressions are deduced, including power...
expression, loads expression, and vibration expressions of blade and tower. Then, the power control strategy based on the collective pitch control and the joint power and loads control strategy using individual pitch control are analyzed; the corresponding system control models are established, too. Both the dynamic characteristics of the collective pitch control and that of the individual pitch control are obtained by virtue of the dynamic characteristic simulations of pitch control.

2 Wind Turbines Coordinate Systems

The loads acting on wind turbines vary continuously and are the major influence factors on the dynamic behaviors of wind turbines. The loads include mainly aerodynamic loads, gravitational loads, and inertial loads. For better calculation and analysis, the wind turbines coordinate systems are established (illustrated in Fig. 1). In the coordinate system \(x_1y_1z_1\), the loads acting on a section of blade element can be decomposed into six components: the force \(F_x\) and moment \(M_y\) along \(x\) axis, the force \(F_y\) and moment \(M_x\) along \(y\) axis, and the force \(F_z\) and moment \(M_z\) along \(z\) axis.

In Fig. 1, \(\gamma\) angle and \(\tau\) angle are the cone angle and tilt angle of the rotor, respectively. The coordinate system \(x_2y_2z_2\) is an inertial coordinate system and fixed at the base of the tower. The coordinate system \(x_3y_3z_3\) is fixed in the nacelle; its \(y_3\) axis is along the shaft axis. The coordinate system \(x_4y_4z_4\) is fixed on the rotor shaft, rotating synchronously with the rotor shaft (angular speed \(\omega\)). Assuming there is no tilt angle, \(x_5y_5z_5\) will change into \(x_5y_5z_5\). The coordinate system \(x_6y_6z_6\) is placed at the rotational blade element; its \(x_6\) axis is perpendicular to \(y_6\) axis and \(z_6\) axis; \(y_6\) axis is perpendicular to \(z_6\) axis and pointing toward the tower (upwind turbines); \(z_6\) axis is along the pitch axis [11].

Regardless of the exception of the origin position between the coordinate systems \(x_1y_1z_1\) and \(x_2y_2z_2\), first the coordinate system \(x_1y_1z_1\) can be obtained when the coordinate system \(x_2y_2z_2\) rotates about the \(x\) axis and along the \(y\) axis with the angle \(\tau\) and \(\gamma\) (\(\tau_{1g}\) is the tower deformation rotating about the \(x\) axis and along the \(y\) axis). Then the coordinate system \(x_3y_3z_3\) can be obtained when the coordinate system \(x_2y_2z_2\) rotates about the \(y\) axis with the angle \(\theta_{gy}\) (\(\theta_{gy}\) is the tower deformation rotating about the \(y\) axis and along the \(x\) axis). Finally, the coordinate system \(x_4y_4z_4\) can be obtained when the coordinate system \(x_3y_3z_3\) rotates about the \(z\) axis with the angle \(\psi\) (yaw angle). The different coordinate values for the same vector in different coordinate systems can be obtained by the transformation matrix.

In order to calculate the aerodynamic loads, both the blade element model (BEM) [12] theory and computational fluid dynamics [13] could be employed. In the early works, a calculation method of aerodynamic loads based on combining BEM theory with dynamic stall model is proposed [11]. Also, the gravitational loads and centrifugal loads calculation expressions are obtained by establishing the corresponding calculation models [14].

3 Pitch Control Objectives Analysis

Pitch control is an important component of the overall wind turbine control systems. Its basic objective is to adjust the wind energy capture or adjust the wind rotor rotational speed. Furthermore, the tower or blade vibration can be suppressed to a certain degree by employing pitch control to adjust the damp of tower or blade subsystem. If the individual pitch control is used, the reduction of wind turbines fatigue loads is an optional objective. In Sec. 3.1, the wind turbine power expression, load expression, blade vibration expression, and tower vibration expression are analyzed.

3.1 Wind Turbines Power Expression. One of the basic purposes of wind turbine control is to control the wind energy capture (maximum or limit). It is feasible to adjust the pitch angle by detecting the generator speed, because according to the operating characteristics of wind turbines, the generator speed can indirectly reflect the captured energy. Of course, it has a certain error due to some uncertain factors. For example, when determining the generator reference speed, the wind speed is the basis which is usually detected by the anemometer installed on the nacelle. The measured wind speed only denotes the wind speed at hub and the actual wind has uneven spatial distribution. Moreover, since the influence of blades rotating, the difference between the detected wind speed and the actual wind speed is large which has been found in wind farm. Thus, it is a better choice to adjust the pitch angle by detecting the actual power. Since the wind turbines power injected into the grid can be detected easily, it can be employed to be the control objective [15,16]. However, since the energy flow system of wind turbines is a large inertia system, there is a time delay between the capture power of wind rotor and power injected into the grid. Furthermore, considering the switch losses of the converter, the pitch control strategy based on the power (injected into the grid) feedback control may cause a large error. So, in this paper, the actual capture power of wind rotor is employed to be the control objective. The calculation method is as follows.

Based on the model of PMSGs, the electromagnetic torque expression of PMSG can be written as

$$T_{ek} = \frac{3}{2} p [\Psi_i L_1 + (L_2 - L_3)] I_d I_q \tag{1}$$

where \(p\) is the pole pairs, \(I_d, I_q\) are the d-axis component and q-axis component of stator current, \(L_1, L_2, L_3\) are the d-axis component and q-axis component of inductance, \(\Psi_i\) is the rotor flux.
These parameters can be determined based on the given motor parameters and online measurement.

The wind rotor torque expression can be written as

$$ T_x = T_{x0} + (J_g + J_y) \frac{d\omega}{dt} $$

(2)

where $J_{ro}$ and $J_{g}$ are the inertial moments of wind rotor and generator rotor, respectively; $\omega$ is the wind rotor angular speed.

Based on the above expressions, the capture power of wind rotor can be expressed as

$$ P = T_x \omega $$

(3)

### 3.2 Loads and Vibration Expressions

The main objective of loads reduction control is to reduce the fatigue loads on the key components of wind turbines. Usually, the tilt moment and yaw moment on the hub or nacelle are employed to measure the fatigue loads on wind turbines. Based on the coordinate systems for wind turbines illustrated in Fig. 1, the dynamic equations are established. Some hypotheses are given, such as not considering the yaw motion and nacelle motion, using edgewise direction elastic hinge model and flapwise direction elastic hinge model to represent the joint of blade root and hub, using the sideward direction elastic hinge model and fore-aft direction elastic hinge model to represent the joint of tower bottom and ground, considering the torsion stiffness and damp of the rotor shaft, assuming the nacelle and tower rigid coupling.

#### 3.2.1 Blade and Tower Dynamic Equations in Blade Edgewise Direction and Tower Sideward Direction

Assuming the blade angular deformation is $\theta_{bx}$ along $x_b$ axis in coordinate system $x_b, y_b, z_b$, one gets

$$ \ddot{\theta}_{bx} + c_{bx} \dot{\theta}_{bx} + k_{bx} \theta_{bx} = -M_{y_b} $$

(4)

$$ \ddot{\theta}_{by} + c_{by} \dot{\theta}_{by} + k_{by} \theta_{by} = -M_{z_b} $$

(5)

$$ \ddot{\theta}_{bz} + c_{bz} \dot{\theta}_{bz} + k_{bz} \theta_{bz} = -M_{x_b} $$

(6)

where $M_b$ is blade mass moment of inertia; $C_{bx}$ is damp coefficient of blade edgewise motion; and $k_{bx}$ is stiffness coefficient of blade edgewise motion.

Assuming the tower angular deformation is $\theta_{tx}$ along $x_t$ axis in coordinate system $x_t, y_t, z_t$, one gets

$$ \ddot{\theta}_{tx} + c_{tx} \dot{\theta}_{tx} + k_{tx} \theta_{tx} = F_{x_{tg}}H - M_{y_{tg}} $$

(7)

where $\theta_{tx}$ is tower (including nacelle) mass moment of inertia; $C_{tx}$ is damp coefficient of tower sideward motion; $k_{tx}$ is stiffness coefficient of tower sideward motion; and $H$ is tower height.

The expression of $F_{x_{tg}}$ in Eq. (7) can be obtained by coordinate transformation matrix. Since $F_{x_{tg}} = \mathbf{A}_{x_{tg}}^T \mathbf{F}_x$ \cite{11}, one gets

$$ \begin{bmatrix} F_{x_{tg}} \\ F_{y_{tg}} \\ F_{z_{tg}} \end{bmatrix} = \begin{bmatrix} \cos(v) & -\sin(v) & 0 \\ \sin(v) & \cos(v) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos(w) & 0 & -\sin(w) \\ 0 & 1 & 0 \\ -\sin(w) & 0 & \cos(w) \end{bmatrix} \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} $$

(8)

where $v$ is the yaw angle and $w(=\omega t)$ is the rotor rotational angle.

Based on Eq. (8), $F_{x_{tg}}$ can be expressed as

$$ F_{x_{tg}} = \cos(v) \cos(w) F_x - \sin(v) F_y - \cos(v) \sin(w) F_z $$

(9)

where $F_x$, $F_y$, and $F_z$ are the components of resultant force from all blades.

In order to calculate the $F_x$, $F_y$, and $F_z$, the coordinate transformation equation $F_x = A_{x_b}^T F_x$ can be used. Then one gets

$$ \begin{bmatrix} F_{x}\n F_{y}\n F_{z} \end{bmatrix} = \begin{bmatrix} \cos(\Theta) & 0 & -\sin(\Theta) \\ \sin(\Theta) \sin(\gamma_0) & \cos(\Theta) \sin(\gamma_0) & \cos(\Theta) \cos(\gamma_0) \\ \sin(\Theta) \cos(\gamma_0) & -\sin(\gamma_0) & \cos(\Theta) \cos(\gamma_0) \end{bmatrix} \begin{bmatrix} F_{x_{tg}} \\ F_{y_{tg}} \\ F_{z_{tg}} \end{bmatrix} $$

(10)

Equations (10) can be rewritten as

$$ \begin{align*}
F_x &= \sum_{i=1}^{3} (\cos(\Theta_i) F_{x_{tg_i}} - \sin(\Theta_i) F_{z_{tg_i}}) \\
F_y &= \sum_{i=1}^{3} (\sin(\Theta_i) \sin(\gamma_0) F_{x_{tg_i}} + \cos(\Theta_i) F_{y_{tg_i}} + \cos(\Theta_i) \sin(\gamma_0) F_{z_{tg_i}}) \\
F_z &= \sum_{i=1}^{3} (\sin(\Theta_i) \cos(\gamma_0) F_{x_{tg_i}} - \sin(\gamma_0) F_{y_{tg_i}} + \cos(\Theta_i) \cos(\gamma_0) F_{z_{tg_i}})
\end{align*} $$

(11)

Substituting Eq. (11) into Eq. (10), one has

$$ F_{x_{tg}} = \cos(v) \cos(w) M_{xs} + \cos(v) M'_{ys} - \sin(v) F_{w_z} $$

(12)

Since the coordinate transformation matrix in Eq. (8) is also applicable to the moment, $M_{y_{tg}}$ can be expressed as

$$ M_{y_{tg}} = \sin(v) \cos(w) M_{xs} + \cos(v) M'_{ys} - \sin(v) \sin(w) M_{zs} + \sin(v) M'_{x_s} + \cos(v) M'_{y_s} $$

(13)

In Eq. (12), the front half part is from the moment acting on wind turbines blades, the last half part that is underlined is from the forces acting on wind turbines blades. In the front half part of the moment expression, the relationship between $M'_{y_s}$ and $M_y$ can be written as

$$ M_{y_{tg}} = \cos(v) \cos(w) M_{xs} + \cos(v) M'_{ys} - \sin(v) F_{w_z} $$

(14)
Based on the coordinate transformation equation \( \mathbf{M}_e = A_2^T \mathbf{M}_b \), one gets

\[
\begin{align*}
M_{x_1} &= \sum_{i=1}^{3} (\cos(\Theta_i)M_{x_{ei}} - \sin(\Theta_i)M_{z_{ei}}) \\
M_{y_1} &= \sum_{i=1}^{3} (\sin(\Theta_i) \sin(\gamma_0)M_{x_{ei}} + \cos(\gamma_0)M_{y_{ei}}) \\
&\quad + \cos(\Theta_i) \sin(\gamma_0)M_{z_{ei}} \\
M_{z_1} &= \sum_{i=1}^{3} (\sin(\Theta_i) \cos(\gamma_0)M_{x_{ei}} - \sin(\gamma_0)M_{y_{ei}}) \\
&\quad + \cos(\Theta_i) \cos(\gamma_0)M_{z_{ei}}
\end{align*}
\]  

(15)

where the relationship between \( M'_{x_{ei}} \) and \( M_{x_{ei}} \) is determined based on the following blade flap motion equation: \( \gamma_{yi} = - (c_{yi} \beta_{yi} + k_{yi} \dot{\beta}_{yi}) \); the relationship between \( M'_{z_{ei}} \) and \( M_{z_{ei}} \) can be expressed approximately as \( M'_{z_{ei}} = M_{z_{ei}} - J_s \frac{\dot{\theta}_{yi}}{\dot{\beta}_{yi}}/dt \), where \( J_s \) is the moment of inertia about the pitch axis, \( \omega_{yi} \) is the pitch rate of the \( i \)th blade.

\[
\begin{align*}
M'_{x_{1}} &= \sum_{i=1}^{3} (\cos(\Theta_i)M_{x_{ei}} - \sin(\Theta_i)M_{z_{ei}}) \\
M'_{y_{1}} &= \sum_{i=1}^{3} (\sin(\Theta_i) \sin(\gamma_0)M_{x_{ei}} + \cos(\gamma_0)M_{y_{ei}}) \\
&\quad + \cos(\Theta_i) \sin(\gamma_0)M_{z_{ei}} \\
M'_{z_{1}} &= \sum_{i=1}^{3} (\sin(\Theta_i) \cos(\gamma_0)M_{x_{ei}} - \sin(\gamma_0)M_{y_{ei}}) \\
&\quad + \cos(\Theta_i) \cos(\gamma_0)M_{z_{ei}}
\end{align*}
\]

(16)

where \( L \) is the length from hub to tower top.

3.2.2 Blade and Tower Dynamic Equations in Blade Flapwise Direction and Tower Fore-Aft Direction

Assuming the blade angular deformation is \( \gamma_{yi} \) along \( y_i \) axis in coordinate system \( x_i y_i z_i \), one gets

\[
\begin{align*}
\dot{\gamma}_{y1} + c_{yi} \dot{\gamma}_{y1} + k_{yi} \ddot{\gamma}_{y1} &= M_{x_{1}} \\
\dot{\gamma}_{y2} + c_{yi} \dot{\gamma}_{y2} + k_{yi} \ddot{\gamma}_{y2} &= M_{y_{1}} \\
\dot{\gamma}_{y3} + c_{yi} \dot{\gamma}_{y3} + k_{yi} \ddot{\gamma}_{y3} &= M_{z_{1}}
\end{align*}
\]  

(17)

(18)

(19)

where \( c_{yi} \) is damp coefficient of blade flapwise motion and \( k_{yi} \) is stiffness coefficient of blade flapwise motion.

Based on Eqs. (17)–(19), one has \( M_{x_{1}} = c_{yi} \dot{\gamma}_{yi} + k_{yi} \ddot{\gamma}_{yi} \).

Assuming the tower angular deformation is \( \gamma_{ti} \) along \( y_t \) axis in coordinate system \( x_t y_t z_t \), one gets

\[
\begin{align*}
\dot{\gamma}_{y1} + c_{yi} \dot{\gamma}_{y1} + k_{yi} \ddot{\gamma}_{y1} &= F_{y1} + M_{x_{1}} \\
\dot{\gamma}_{y2} + c_{yi} \dot{\gamma}_{y2} + k_{yi} \ddot{\gamma}_{y2} &= F_{y2} + M_{y_{1}} \\
\dot{\gamma}_{y3} + c_{yi} \dot{\gamma}_{y3} + k_{yi} \ddot{\gamma}_{y3} &= F_{z1} + M_{z_{1}}
\end{align*}
\]  

(20)

In Eq. (20), \( F_{y1} \) and \( M_{x_{1}} \) can be obtained based on the following methods. From the coordinate transformation equation \( \mathbf{F}_1 = A_2^T A_{20}^T A_{1}^T \mathbf{F}_e \), one has

\[
\begin{bmatrix}
F_{x1} \\
F_{y1} \\
F_{z1}
\end{bmatrix} =
\begin{bmatrix}
\cos(\theta_{x1}) & 0 & \sin(\theta_{x1}) \\
0 & 1 & 0 \\
\sin(\theta_{x1}) & 0 & -\cos(\theta_{x1})
\end{bmatrix}
\begin{bmatrix}
\cos(v) & -\sin(v) & 0 \\
\sin(v) & \cos(v) & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
F_{x_e} \\
F_{y_e} \\
F_{z_e}
\end{bmatrix}
\]  

(21)

From Eq. (21), Eq. (22) can be obtained

\[
F_{y1} = \sin(v) \cos(w) F_{x_e} + \cos(v) F_{y_e} - \sin(v) \sin(w) F_{z_e}
\]  

(22)

Substituting Eq. (11) into Eq. (22), one has

\[
\begin{align*}
F_{y1} &= \sin(v) \cos(w) F_{x_e} - \sin(v) \sin(w) F_{z_e} \\
&\quad + \cos(v) \sum_{i=1}^{3} (\sin(\Theta_i) \sin(\gamma_0) F_{x_{ei}} + \cos(\gamma_0) F_{y_{ei}}) \\
&\quad + \cos(\Theta_i) \sin(\gamma_0) F_{y_{ei}} + \cos(\Theta_i) \cos(\gamma_0) F_{z_{ei}}
\end{align*}
\]  

(23)

The coordinate transformation matrix in Eq. (21) is also applicable to moment transformation. \( M_{x_{1}} \) can be expressed as

\[
\begin{align*}
M_{x_{1}} &= (\cos(\theta_{x1}) \cos(v) \cos(w) + \sin(\theta_{x1}) \sin(w)) M_{x_e} \\
&\quad - \sin(\theta_{x1}) \sin(v) M_{y_e} + (\cos(\theta_{x1}) \cos(v) \sin(w) + \sin(\theta_{x1})\cos(v)) M_{z_e}
\end{align*}
\]  

(24)

In Eq. (24), the front half part is from the moment acting on wind turbines blades, the last half part that is underlined is from the forces acting on wind turbines blades. The relationship between \( M_{y_{1}} \) and \( M_{z_{1}} \) is denoted by Eq. (13); the relationship between \( M_{x_{1}} \) and \( M_{y_{1}} \) is denoted by Eq. (15); the relationship between \( M_{x_{1}} \) and \( M_{y_{1}} \) is denoted by Eq. (16). \( M_{x_{1}} \) can be denoted by

\[
\begin{align*}
M'_{x_{1}} &= F_{x1} = \cos(w) F_{x_e} - \sin(w) F_{z_e} \\
&\quad - \cos(v) \sum_{i=1}^{3} (\cos(\Theta_i) F_{x_{ei}} - \sin(\Theta_i) F_{z_{ei}}) \\
&\quad - \sin(w) \sum_{i=1}^{3} (\sin(\Theta_i) \cos(\gamma_0) F_{x_{ei}} - \sin(\gamma_0) F_{y_{ei}}) \\
&\quad \cdot F_{y1} + \cos(\Theta_i) \cos(\gamma_0) F_{z_{ei}}
\end{align*}
\]  

(25)

Based on the above-mentioned deduction, the corresponding expressions are obtained, such as tilt moment expression \( M_{x_t} \) on the hub, yaw moment expression \( M_{z_t} \), on the hub, blade vibration expression, and tower vibration expression.

4 Pitch Control Strategy for Directly Driven PMSG Wind Turbines

A control scheme case of directly driven PMSG wind turbines is illustrated in Fig. 2. The main control loops include electric control loop (converter control, electromagnetic torque control, and pitch control loop).

---

**Fig. 2** Control scheme of directly driven PMSG wind turbines
control, etc.) and pitch control loop. The researches on modelling and control of wind turbines electrical system have been carried out by many researchers [17,18]. The following analysis mainly aims at the pitch control strategy.

4.1 Power Control Strategy Based on the Collective Pitch Control. When the fatigue loads reduction and vibration reduction are not considered, only the power control is considered, the collective pitch control can be used. In this paper, the discussion on power control is limited on the range that the inflow wind speed exceeds its rated speed. The wind energy capture rate is controlled by pitch angle adjustment, and the wind energy capture objective is the minimum power fluctuation according to the rated power. If the designed wind energy capture power is $P^*$ and the actual capture power is $P$, the pitch control objective can be designed as

$$\min|P - P^*| \rightarrow 0 \quad (26)$$

Since the aerodynamic torque decreases with the increasing of pitch angle, based on the PI controller the pitch angle control model can be established as

$$\beta^* = K_{cp}(P - P^*) + K_{ci}\int (P - P^*) \quad (27)$$

where $K_{cp}, K_{ci}$ are the proportional coefficient and integral coefficient, respectively.

The PI controller scheme for collective pitch control is illustrated in Fig. 3. Figure 4 is the collective pitch control scheme of directly driven PMSG wind turbines. In Fig. 4, the error between the feedback value and command value of the wind rotor rotational speed enters the PI controller and then produces the command torque of generator. Based on the generator-side controller, the command torque of generator is transformed into pulse width modulated signal to control the power transistor switch action, thereby realizing torque control and ensuring that the rotational speed of the rotor is almost constant. When the wind speed varies, only the pitch control is employed to adjust the wind energy capture power and output. When the pitch control command $\beta^*$ passes through the pitch actuator, three blade pitch angles $\beta_1$, $\beta_2$, and $\beta_3$ are obtained.

4.2 Joint Power and Loads Control Based on Individual Pitch Control. The above-mentioned power control strategy has simple pitch control scheme, but neglects fatigue loads on wind turbines. For modern large scale wind turbines, the wind shear effect and tower shadow effect will produce significant fatigue loads which influence the life of wind turbines. Therefore, joint power and loads control are quite necessary which means that each blade has individual pitch actuator and the pitch angle of different blades is unsynchronized. It should be pointed out that fatigue loads on wind turbines can be seen from different angles, such as the edgewise or flapwise moment fluctuations on single blade, the tilt or yaw moment fluctuations on hub or nacelle. For the sake of convenience analysis and establishment of control strategies, the blade edgewise moment is employed to be the direct control variable and the tilt and yaw moment fluctuations on hub are employed to be the performance indicators.

In an optimal situation, the minimum power fluctuations and load fluctuations are expected to achieve synchronously. The pitch control objective is designed as

$$\begin{align*}
\min|P - P^*| & \rightarrow 0 \\
\min[\max M_{yer} - \min M_{yer}] & \rightarrow 0, \quad i = 1, 2, 3 \quad (28)
\end{align*}$$

where $\max M_{yer}$, $\min M_{yer}$ are the maximum and minimum blade root edgewise moment of blades $i$ ($i = 1, 2, 3$) in the process of blade rotating 360 deg, respectively.

In order to realize the pitch control objective expressed in Eq. (28), some control methods can be employed, such as multi objective optimization control, converting a multi objective control into a single objective control. What deserves special mention is that in the field of individual pitch control research, many researchers have carried out the research works from different angles, including LQG control method and multivariable $H_{\infty}$ control method. Many methods are based on the state equation of wind turbines. However, wind turbines are multidimensional and higher order nonlinear systems which include multiphysics field and multiphysics processes. Especially in the actual operation process, it is...
rather difficult to obtain the accurate state equation and to design accurately the controller.

In many literatures, the tilt moment and yaw moment are employed to be the feedback signals of fatigue loads control that based on individual pitch control. Since these two variables are difficult to be measured directly, usually a linear model of wind turbines is used to calculate indirectly the tilt moment and yaw moment and calculation errors are inevitable. In order to overcome the system defects caused by the calculation errors, the directly measured blade root edgewise moment \( M_{\text{b}} \) is introduced into the wind turbine. Early the coordinate transformation is mainly used in motor control and is introduced into the wind turbine to the coordinate transformation principle, the relationships are determined by the initial blade location. Accordingly, the coordinate transformation is a typical individual pitch control method [1,2]. The base value \( \beta^* \) of pitch angle command is produced based on the expression \( \beta^* = \min \{ \beta \} \). The above-mentioned implementation scheme includes: (1) the base value \( \beta^* \) of pitch angle command is produced based on the expression \( \min \{ \beta \} \); (2) the incremental values \( \Delta \beta^i \), \( \Delta \beta^i \), and \( \Delta \beta^i \) of three pitch angle commands are produced based on the expression \( \min \{ \beta \} \); (3) the actual values \( \beta^i \), \( \beta^i \), and \( \beta^i \) of three pitch angle commands are obtained by superposing \( \Delta \beta_{\text{abc}}(i = 1, 2, 3) \) over \( \beta^* \). The pitch angle commands \( \beta^i \), \( \beta^i \), and \( \beta^i \) are the inputs of pitch actuators. The above-mentioned implementation scheme is a typical individual pitch control method [1,2] and its control scheme is shown in Fig. 5. The base value \( \beta^* \) of pitch angle command is obtained based on Eq. (27) and the PI controller is shown in Fig. 3.

In Sec. 5, the producing mechanism on the incremental values \( \Delta \beta^i \), \( \Delta \beta^i \), and \( \Delta \beta^i \) is analyzed. First, supposing the blade root edgewise moment \( M_{\text{b}} \), \( M_{\text{b}} \), and \( M_{\text{b}} \) have been measured by the sensor. Considering the wind shear effect, the three moments change periodically with the wind rotor rotation angle. Since a wind rotor with three blades, azimuth angles are 120 deg apart from each of them, \( M_{\text{b}} \), \( M_{\text{b}} \), \( M_{\text{b}} \), and \( M_{\text{b}} \) in three phase coordinate system \( abc \) can be employed to denote the three blade edgewise moments, respectively, and the corresponding relationships are determined by the initial blade location. According to the coordinate transformation principle, \( M_{\text{b}} \), \( M_{\text{b}} \), and \( M_{\text{b}} \) can be transformed into \( M_{\text{b}} \) and \( M_{\text{b}} \) which are in two-phase rotating coordinate system \( dq \). Early the coordinate transformation is mainly used in motor control and is introduced into the wind turbine load control by researchers later [1–3]. The transformation method can be expressed as

\[
M_d = \frac{2}{3} \left[ M_a \sin(\omega t) + M_b \sin \left( \omega t - \frac{2\pi}{3} \right) + M_c \sin \left( \omega t + \frac{2\pi}{3} \right) \right]
\]

\[
M_q = \frac{2}{3} \left[ M_a \cos(\omega t) + M_b \cos \left( \omega t - \frac{2\pi}{3} \right) + M_c \cos \left( \omega t + \frac{2\pi}{3} \right) \right]
\]

In ideal condition, the blade root edgewise moments will keep constant when the wind rotor rotation angle varies that means both \( M_d \) and \( M_q \) are zero. However, in actual condition both \( M_d \) and \( M_q \) are not zero. In order to eliminate the error, the pitch angle \( \beta \) is adjusted instantaneously in individual pitch control strategy.

Based on the design principle of PI controller, in two-phase rotating coordinate system \( dq \), \( \Delta \beta_d^i \) and \( \Delta \beta_q^i \) are expressed as

\[
\Delta \beta_d^i = K_{\text{pd}} M_d + K_{\text{pi}} \int M_d \, dt \quad (31)
\]

\[
\Delta \beta_q^i = K_{\text{pq}} M_q + K_{\text{qi}} \int M_q \, dt \quad (32)
\]

Based on coordinate transformation, \( \Delta \beta_d^i \) and \( \Delta \beta_q^i \) can be transformed into \( \Delta \beta_{\text{abc}}^i \), \( \Delta \beta_{\text{abc}}^i \), and \( \Delta \beta_{\text{abc}}^i \) in three phase coordinate system \( abc \). The transformation equation is as follows:

\[
\begin{align*}
\Delta \beta_{\text{abc}}^i &= \Delta \beta_d^i \sin(\omega t) + \Delta \beta_q^i \cos(\omega t) \\
\Delta \beta_{\text{abc}}^i &= \Delta \beta_d^i \sin \left( \omega t - \frac{2\pi}{3} \right) + \Delta \beta_q^i \cos \left( \omega t - \frac{2\pi}{3} \right) \\
\Delta \beta_{\text{abc}}^i &= \Delta \beta_d^i \sin \left( \omega t + \frac{2\pi}{3} \right) + \Delta \beta_q^i \cos \left( \omega t + \frac{2\pi}{3} \right)
\end{align*}
\]

Combining Eqs. (33) and (27), the pitch angle command of each blade is written as

\[
\begin{align*}
\beta_{\text{abc}}^i &= \frac{1}{\tau_s + 1} \beta_{\text{abc}}^i \\
\beta_{\text{abc}}^i &= \frac{1}{\tau_s + 1} \beta_{\text{abc}}^i \\
\beta_{\text{abc}}^i &= \frac{1}{\tau_s + 1} \beta_{\text{abc}}^i
\end{align*}
\]

In Eq. (34), \( \beta_{\text{abc}}^i \), \( \beta_{\text{abc}}^i \), and \( \beta_{\text{abc}}^i \) are corresponding to \( M_{\text{b}} \), \( M_{\text{b}} \), and \( M_{\text{b}} \), respectively.

The established individual pitch control structure of directly driven PMSG wind turbines is illustrated in Fig. 6.

In Fig. 6, the pitch angle command will be transformed into the actual blade pitch angle via the pitch actuator. The pitch actuator is usually actualized by a hydraulic device or an electric mechanism and denoted by a first order, a second order, or higher order transfer function. Using a first order lag transfer function, one gets

\[
\beta_{\text{abc}}(s) = \frac{1}{\tau_s + 1} \beta_{\text{abc}}(s)
\]

where \( \tau \) is the time constant.

From Eq. (35), it can be seen that there has certain difference between the pitch angle command value and actual value. When adjusting the pitch angle, the pitch actuator dynamic characteristics will influence the adjusting effects. Considering that it is difficult to describe the dynamic characteristics using the simplified transfer function, such as Eq. (35), a more complex dynamic and control model is employed and the scheme is illustrated (Fig. 7).
In the figure, \( x, p \) denote the sun gear and planetary gear; the ring gear \( r \) is fixed. Through the motor shaft, planetary gearbox, and drive pinion \( z_1 \), the torque produced by the drive motor is delivered to the inner toothing \( z_2 \) and drives the blade to rotate around the pitch axis. By comparing the pitch angle command \( \beta^* \) with the measured pitch angle \( \beta \), the pitch actuator controller outputs the control signal to the drive motor.

The motion differential equations can be written as

\[
\begin{align*}
J_m \ddot \theta_m + c_1 (\dot \theta_m - \dot \theta_s) + k_1 (\theta_m - \theta_s) &= T_i \\
J_s \ddot \theta_s + c_1 (\dot \theta_s - \dot \theta_m) + k_1 (\theta_s - \theta_m) + \sum_{j=1}^3 (c_{p_j} \dot \theta_j \dot \theta_j^* r_{m_j}) &= 0 \\
&\quad + k_{p_j} \dot \theta_j^* r_{m_j}, \\
J_{Z2} \ddot \theta_{Z2} - r_{Z2} \dot \theta_{Z2} (r_{Z2} \dot \theta_{Z2} - r_{Z2} \dot \theta_{Z2}) - r_{Z2} \dot \theta_{Z2}^2 \dot f(\dot x) &= -T_L \\
\ddot x &= b_1, \quad \ddot x \geq b_1, \\
\ddot x + b_1, \quad -b < \ddot x < b \\
f(\dot x) &= \begin{cases} 0, & \ddot x \geq b_1; \\
\ddot x + b_1, & -b < \ddot x < b \\
\ddot x - b, & \ddot x \leq -b 
\end{cases}
\end{align*}
\]

where \( J_m \) is the inertia moment of drive motor; \( J_s \) is the inertia moment of sun gear 1; \( J_{Z2} \) is the pitch inertia moment of blade; \( c_1 \),

\( k_1 \) are the equivalent damping and stiffness coefficients of motor output shaft; \( c_{p_j}, k_{p_j} \) are meshing damping coefficients and stiffness coefficients of gear pairs; \( c_{Z1}, k_{Z1} \) are the meshing damping and stiffness coefficients between drive pinion \( z_1 \) and inner toothing \( z_2 \); \( r_{m_j} \) is the base circle radius of sun gear; \( r_{Z2} \) are the base circle radii of drive pinion \( z_1 \) and inner toothing \( z_2 \); \( T_i, T_L \) are the motor output torque and load torque of drive system; \( x_p, y_p \) is the relative displacement of gear teeth; \( \dot x \) is the relative displacement between drive pinion \( z_1 \) and inner toothing \( z_2 \); \( f(\dot x) \) is gap function; \( e_{p_j} \) is relative synthetic error; and \( b \) is gear backlash.

Using Eq. (36), the more accurate performance characteristics of the pitch actuator controller can be described. In addition, the more detailed dynamic and control model is in Ref. [19].

5 Simulation Analyses of Pitch Control

In order to analyze the dynamic characteristics of pitch control, the system simulation model for an MW scale directly driven PMSG wind turbines is established in Simulink. Since the mathematical model of wind turbines includes multiple sub-processes which interact on each other and have different rates of change, it is a rigid system. The variable-step ode23tb (stiff/TR-backward differentiation formula (BDF2)) arithmetic that is suitable for stiff problems is employed to solve the model. The arithmetic is an implicit Runge-Kutta formula with a trapezoidal rule first stage, and a second stage consisting of a BDF of order two. At crude tolerances, BDF2 is more effective than numerical differentiation formulas.

The main wind turbines parameters used in simulation model are shown in Table 1; the stiffness coefficients are assumed to be large enough. Based on the pitch control strategies established in this paper, both the collective pitch control simulation and individual pitch control simulation are carried in the following section. The given wind rotor rotational speed is 17 rpm, the power command is 1.2 MW, and the reactive power command injected into grid is zero.

The given wind speed at hub is shown in Fig. 8(a). Wind speed progressively increases from 12 m/s to 14 m/s and its space distribution is assumed to obey the Holman law (exponent 0.2). Figure 8(b) shows the varied pitch angle curves corresponding to the varied wind speed. At the wind speed range that is higher than its speed rating, the pitch angle will increase with the increase in wind speed and will decrease with the decrease in wind speed. Since the late effect of pitch actuator, the pitch angle variation lags the wind speed variation. For the collective pitch control, the pitch angle regulation is mainly relevant to the inflow speed. For the individual pitch angle regulation, the pitch angle regulation is...
tude falls 10% which is defined as the percentage of difference
Compared with constant pitch angle control, the fluctuation ampli-
control is used, the power fluctuation range is 1.08 MW–1.28 MW.
At the condition of collective pitch control. If the individual pitch
range 1.1 MW–1.43 MW and the range is 1.08 MW–1.31 MW
fluctuates in the range
wind rotor rotational speed constant. From Fig. 9(0
b
=a =
= C0
b
C0
b
Nm s/rad Tower and nacelle moment of inertia around the ground 4.6724 × 10^8 kg m^2
Table 1 Wind turbine simulation parameters
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>1.2 MW</td>
<td>Tower flapwise damping coefficient</td>
<td>3.3 × 10^8 Nm s/rad</td>
</tr>
<tr>
<td>Rated wind speed</td>
<td>12 m/s</td>
<td>Blade edgewise stiffness coefficient</td>
<td>3.58 × 10^8 Nm/rad</td>
</tr>
<tr>
<td>Wind rotor diameter</td>
<td>62 m</td>
<td>Blade flapwise stiffness coefficient</td>
<td>1.6 × 10^8 Nm/rad</td>
</tr>
<tr>
<td>Wind rotor rotational speed</td>
<td>11–20 rpm</td>
<td>Tower edgewise stiffness coefficient</td>
<td>5.5 × 10^8 Nm/rad</td>
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<tr>
<td>Wind rotor moment of inertia</td>
<td>2.5 × 10^6 kg m^2</td>
<td>Tower height</td>
<td>67.8 m</td>
</tr>
<tr>
<td>Blade edgewise damping coefficient</td>
<td>1.8 × 10^6 Nm s/rad</td>
<td>Nacelle length</td>
<td>3 m</td>
</tr>
<tr>
<td>Tower edgewise damping coefficient</td>
<td>3.3 × 10^6 Nm s/rad</td>
<td>Nacelle length</td>
<td>3 m</td>
</tr>
</tbody>
</table>

Fig. 8 Wind speed and actual pitch angle: (a) wind speed at hub and (b) actual pitch angle of blade

Fig. 9 Wind rotor rotational speed and power injected into grid: (a) wind rotor rotational speed and (b) power injected into grid

not only relevant to the inflow speed but also relevant to the azi-
angle. The actual pitch angle is not completely equal to its
instruction value. It is influenced by the response characteristic of
the pitch actuator [19] and by the pitch rate \( \frac{d(\beta + \Delta\beta)}{dt} \).
Figure 9(a) shows the wind rotor rotational speed curves and
Fig. 9(b) shows the curves of power injected into grid. When the
wind speed is higher than its speed rating, the pitch control is used
to adjust the amount of wind energy capture and keep the wind
rotor rotational speed constant. From Fig. 9(a), it can be seen that
using whether collective pitch control or individual pitch control
the wind rotor rotational speed fluctuates in the range
17.13 rpm–17.21 rpm. Compared with the instruction value
17 rpm, the fluctuation amplitude is 0.4% and the maximum devi-
ation is 1.17%. In order to illuminate the pitch control necessity,
the power curves injected into grid are given in Fig. 9(b) at differ-
ent conditions, including constant pitch angle control (pitch angle
\( \beta = 0 \) deg), collective pitch control, and individual pitch control.
At the condition of constant pitch angle, the power fluctuates in
the range 1.1 MW–1.43 MW and the range is 1.08 MW–1.31 MW
at the condition of collective pitch control. If the individual pitch
control is used, the power fluctuation range is 1.08 MW–1.28 MW.
Compared with constant pitch angle control, the fluctuation ampi-

between the maximum and minimum values and the command
value; the maximum deviation falls 12.5%. Based on the above-
mentioned analyses, it can be known that both the collective pitch
control and individual pitch control can level off power output.

Figure 10 shows single blade root bending moment curves
where the moment consists of the moment formed by aerody-
namic force, that formed by gravity and that formed by inertia
force. From the edgewise moment curves illustrated in Fig. 10(a),
it can be seen that the edgewise moment changed periodically
with the running time (azimuth angle) and its range of variation is
–2.6 × 10^8 Nm–7.1 × 10^8 Nm. For different pitch control strat-
egies, the edgewise moment curves are almost coincident. The
edgewise moment mainly comes from the aerodynamic force and
gravity. For MW scale wind turbines, since the blade mass is
much large, the moment formed by gravity occupies the dominant
position. Furthermore, since the aerodynamic force is mainly
influenced by the pitch angle regulation, the edgewise moment
has little variation when regulating the pitch angle. For the flap-
wise moment, since aerodynamic force had a significant effect, it
has obvious change when regulating the pitch angle.

Figure 10(b) shows that when the individual pitch control is
employed, the variation amplitude of blade root flapwise moment
is about 65% of that when collective pitch control is used where

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the variation amplitude is defined as the difference between the maximum and minimum values of flapwise moment when blade rotating 360 deg and is denoted by “A.” Comparing between Figs. 10(a) and 10(b), it can be known that the edgewise moment variation amplitude of blade root is significantly larger than the flapwise moment variation amplitude. Therefore, the blade edgewise stiffness coefficient should be designed to be larger than the flapwise stiffness coefficient.

The tilt and yaw moment curves are illustrated in Fig. 11. When the individual pitch control strategy is employed, the variation amplitude of tilt and yaw moments falls significantly which means the individual pitch control technology can prolong the service life of wind turbines.

6 Conclusion

In this paper, the pitch control objectives and control variables are discussed. The power stability and fatigue loads reduction are selected to be the control objectives and the corresponding expressions are deduced. Both the power control strategies based on the collective pitch control and the joint power and loads control based on individual pitch control are analyzed; the simulation models are established. The research results show that both the collective pitch control and individual pitch control can effectively level off power output; moreover, the individual pitch control can reduce fatigue loads. The pitch angle regulation is mainly relevant to the inflow speed for the collective pitch control and that is not only relevant to the inflow speed but also relevant to the azimuth angle for the individual pitch angle regulation. In MW scale wind turbines, the edgewise moment formed by gravity occupy the dominant position. Therefore, although the individual pitch control can reduce the variation amplitude of flapwise moment, it has little influence on the edgewise moment.

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