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Individual pitch control for torque fluctuation reduction in large-scale wind turbine generator systems

***Abstract**. In order to capture maximum wind energy, smooth the wind turbine torque fluctuation and eliminate the unbalanced loads on the wind turbine, the individual pitch control strategy which directly controls the edgewise moment is proposed based on the multi-stage dynamic weight coefficient distribution of the pitch angle according to the blade azimuth. In order to verify the effeteness of the proposed individual pitch control, the simulation experiment is carried out on a 2MW wind turbine generator system. And the results show, compared with collective pitch control, the proposed individual pitch control not only regulates and smoothes the wind turbine torque fluctuation, but also indirectly reduces the fluctuation of the blade flapwise moment, the yaw moment and the tilt moment, and greatly improves the power output as well.*

***Streszczenie.** W artykule opisano strategię sterowania kątem natarcia płatami wirnika turbiny wiatrowej w celu lepszej stabilizacji momentu turbiny i eliminacji niezbalansowania obciążenia. Metoda oparta została na wielostopniowej wadze dynamicznej współczynników podziału kąta natarcia, w zależności od azymutu płata. Przedstawiono wyniki badań symulacyjnych sterowania w systemie generatorów wiatrowych o mocy 2MW, potwierdzające jego wysoką skuteczność i zwiększenie generowanej energii elektrycznej. (**Indywidualne sterowanie kątem natarcia w zastosowaniu do systemu generatorów wiatrowych dużej skali – ograniczenie fluktuacji momentu**).*

Keywords: wind turbine torque fluctuation; edgewise moment; individual pitch control; multi-stage dynamic weight coefficient distribution.
Słowa kluczowe: fluktuacje momentu w turbinie wiatrowej, moment graniczny, samodzielne sterowanie kątem natarcia, wielostopniowa waga dynamiczna, współczynnik podziału.

Introduction

With the development of large-scale wind turbine generator system, variable speed pitch control gradually becomes the mainstream [1]. Regardless of electrical servo or hydraulic servo, the pitch actuator mechanism usually uses the collective pitch control strategy (CPC). The CPC is all blades are pitched by the same pitch angle command [2]. Because the wind speed distribution in the wind rotor swept plane is uneven, there are some unbalanced loads generated on large-scale wind turbine. With the increasing capacity of wind turbine, the uneven intensity of aerodynamic forces and the unbalanced loads become serious. The unbalanced loads will bring many problems such as blade vibration, drive train torsion, tower bending, mechanical strength and the power quality [3]-[4]. Therefore, it is more and more necessary to reduce these unbalanced loads by the individual pitch control (IPC). Up to now, the studies of IPC research mainly are focused on the blade flapwise moment regulation to reduce blade flapwise vibration, the tower for-aft bending and the tower side-side bending caused by wind shear, tower shadow and turbulence and so on. These IPC strategies adopt cyclic pitch control [5]-[6], D-Q axis transformation IPC, Coleman transformation IPC, weight distribution IPC, smart rotor control and so on. However, the above control strategies did not consider the generator output fluctuation, the fluctuation of wind turbine torque and blade edgewise moment.

In this paper, the conclusion that the blade edgewise moment fluctuation generated by the aerodynamic force is the main influence factor of the wind turbine torque fluctuation based on the analysis of wind turbine loads is deduced. Therefore a new IPC strategy which directly controls the edgewise moment torque based on the multi-stage dynamic weight coefficient distribution of the pitch angle (MSDWCDPA-IPC) in accordance with the blade azimuth is firstly proposed. Based on the built dynamic aerodynamic wind turbine model, the effect rules of wind turbine torque caused by wind shear, tower shadow, and turbulence are studied. Then the controller with MSDWCD-IPC is designed, and the blade pitch angles are adjusted by dynamic weight coefficient. Finally, the simulation model is set up to verity the correctness. The simulation results show this IPC controller not only directly reduces the wind turbine torque fluctuation and the blade edgewise moment, but also indirectly reduces the fluctuations of the blade flapwise moment, the yaw moment and the tilt moment.

The detailed analysis of wind torque fluctuation and the calculation of loads on blade and wind turbine

Because the kinetic energy of wind can be converted into mechanical energy by the wind turbine generator system, the external loads also act on the blade. Thus the loads on the wind turbine come from the blade loads too. The blade loads are aerodynamic, gravity, inertia and so on, so the blade total edgewise moment is mainly composed of the edgewise moment generated by aerodynamic force on the blade and the edgewise moment generated by the blade gravity neglecting the other blade loads based on aerodynamic theory, which can be expressed as:

$$M_{Edgewise,i} = M_{Gravity,i} + M_{Edge,i} \tag{1}$$

where: $M_{Edgewise,i}$ is the total edgewise moment of blade i-th, $M_{Gravity,i}$ is the gravity moment of blade i-th, $M_{Edge,i}$ is the edgewise moment of blade i-th generated by aerodynamic force. For three-bladed upwind horizontal axis wind turbine, the wind turbine torque is the sum of blade edgewise moment.

$$M_{Turbine} = \sum_{i=1}^{3} M_{Edgewise,i} = \sum_{i=1}^{3} M_{Edge,i} \tag{2}$$

where: $M_{Turbine}$ is wind turbine torque, $\sum_{i=1}^{3} M_{Gravity,i} = 0$. Take the blade of 2MW wind turbine as an example, the blade 1 aerodynamic loads which are affected by wind shear, tower shadow and turbulence are calculated based on the blade element theory according to the blade geometry parameters, the blade aerofoil parameters, the blade mass and the blade stiffness parameters. The relationship among $M_{Edgewise,1}$, $M_{Edge,1}$ and $M_{Gravity,1}$ is shown in Fig.1. Although the $M_{Edge,1}$ is significantly less than the $M_{Gravity,1}$, the former is the main influencing factor and cannot be neglected.

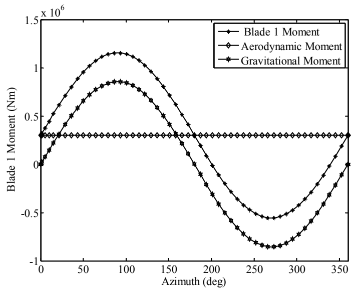
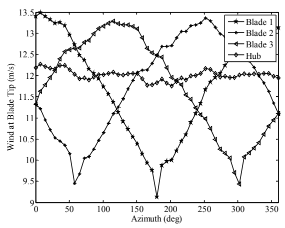
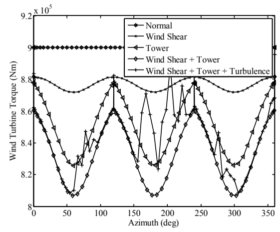


Fig.1. The relationship diagram of the loads on the blade 1

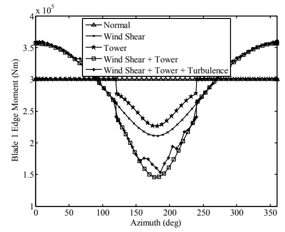
The built dynamic wind turbine aerodynamic model can calculate the aerodynamic forces and the loads on the blade element and the wind turbine according to the specific need, so the wind turbine torque, the loads on the blade 1 and the loads on the tower are calculated by this model with the wind, as shown in Fig.2. The wind turbulence intensity is 0.15, wind shear coefficient is 0.2, and the wind speed of the hub is 12 m/s. The wind speed of the blade tip is shown in Fig.2(a). The fluctuations of the wind turbine torque, the edgewise moment, the flapwise moment, the yaw moment and the tilt moment are proportional to the wind speed variation (the hub curve), as shown in Fig.2 (b) -Fig.2 (f). Moreover wind shear and tower shadow cause the 1 times frequency (1P) fluctuation of the edgewise moment and 1P fluctuation of the flapwise moment, and result in 3 times frequency (3P) fluctuations of the wind turbine torque, the yaw moment and the tilt moment on the tower.



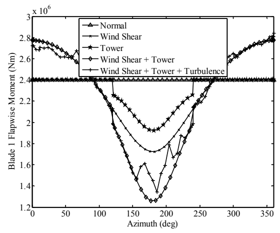
(a) The wind speed at the blade tip



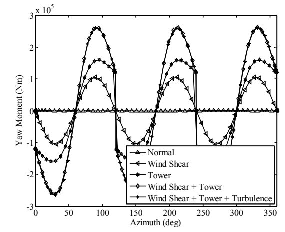
(b) The wind turbine torque



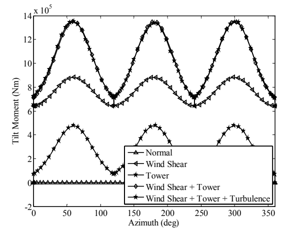
(c) The edgewise moment



(d) The flapwise moment



(e) The yaw moment on the rotor



(f) The tilt moment on the rotor

Fig. 2. The loads on the wind turbine affected by wind shear, tower shadow and turbulence

3. Reducing Wind Torque Fluctuation by IPC

Because the variable of the pitch angle can change the blade attack angle, the normal force coefficient and the lateral force coefficient are regulated, and the force on the blade tends to be uniform, and the blade root moments in the two directions are reduced to a certain extent. Therefore, the IPC can reduce the torque fluctuations of wind turbine and improve the reliability of the wind turbine.

The traditional way to realize the IPC is detecting the blade moments and pitching control individually. But installing some load sensors on the blade is difficult to realize in practice. The most effective way is forecasting the loads on the blade according to the wind speed of the blade element, then adjusting pitch angle individually. In this paper, the dynamic weight coefficients in multi-stage are calculated by the loads on the specific blade element and the wind speed based on the blade azimuth. Thus the pitch angle of each blade is regulated to the individual pitch angle β_i^* base on the collective pitch angle β^* , which can be expressed as: $\beta_i^* = K_i \beta^*$. In order to guarantee the generator output power at the rated power, the weight coefficient K_i adjusted by MSDWCDPA-IPC should meet the following expression:

(3) $$\sum_{i=1}^{3} K_i = 3$$

When the wind rotor rotates, two blades are always in the region where wind shear affects, and the other blade is in the region where tower shadow affects. Neglecting the turbulence effect, the K_i can calculated dynamically according to the blade location. When the blade 1 is in the azimuth range of 0^0 and 120^0 , the k_i can be expressed as:

(4) $$\begin{cases} k_1 = (1 + r\cos\theta/H)^{\alpha} \\ k_2 = 1 + ma^2(y^2 - x^2)/(y^2 + x^2)^2 \\ k_3 = (1 + r\cos(\theta + 240^0)/H)^{\alpha} \end{cases}$$

where: $r = 3R/4$,y is the lateral distance from the blade 1 to tower midline, x is the distance from the blade1 origin to tower midline.

When the blade 1 is in the azimuth range of 120^0 and 240^0 , the k_i can be expressed as:

(5) $$\begin{cases} k_1 = 1 + ma^2(y^2 - x^2)/(y^2 + x^2)^2 \\ k_2 = (1 + r\cos(\theta + 120^0)/H)^{\alpha} \\ k_3 = (1 + r\cos(\theta + 240^0)/H)^{\alpha} \end{cases}$$

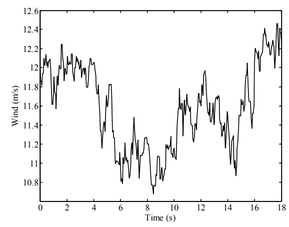
When the blade 1 is in the azimuth range of 240^0 and 360^0 , the k_i can be expressed as:

(6) $$\begin{cases} k_1 = (1 + r\cos\theta/H)^{\alpha} \\ k_2 = (1 + r\cos(\theta + 120^0/H)^{\alpha} \\ k_3 = 1 + ma^2(y^2 - x^2)/(y^2 + x^2)^2 \end{cases}$$

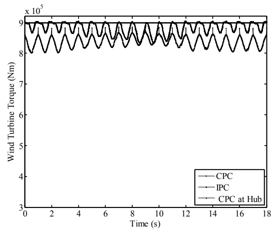
Simulation Result and Analysis

In this paper, the IPC controller with the proposed MSDWCDPA-IPC was tested on a typical 2MW three-blade upwind horizontal axis wind turbine. Fig.3 illustrates the response of the IPC system with the turbulence wind speed. Fig.3 (a) shows the wind speed at the hub. Fig.3 (b), (c), (d), (e) and (f) demonstrate the changes of the wind turbine and blade 1 loads are in accord with the turbulence wind (CPC curve). Furthermore, the fluctuation of the wind turbine, the edgewise moment, the flapwise moment, the tilt moment and the yaw moment reduce significantly by IPC compared to the CPC (IPC curve). Fig.3 (b) illustrates the wind turbine torque fluctuation (CPC curve) is 10% smaller compared the rated torque (CPC at Hub curve). And the wind turbine torque (IPC curve) by proposed IPC tends to the rated torque and the torque fluctuation reduced greatly to 2.8%.

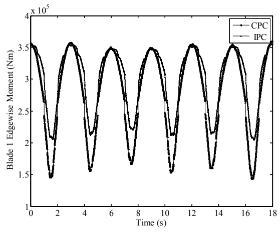
Fig.3 (g) demonstrates the collective pitch angle (CPC curve) changes with the wind speed. The IPC pitch angle (Blade i curve) relates to the wind speed and the blade azimuth. When the blade rotates from the top position to the bottom position in the rotating plane, the pitch angle decreases; and when the blade rotates from the bottom position to the top position, the pitch angle increases.



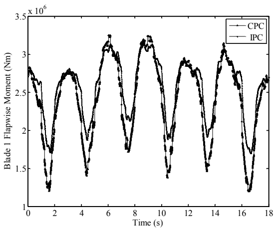
(a) The wind speed at hub



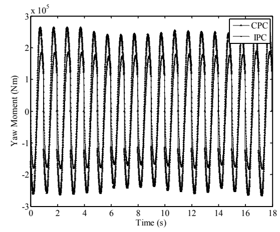
(b) The wind turbine torque



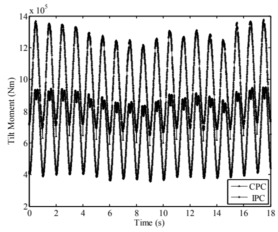
(c) The blade 1 edgewise moment



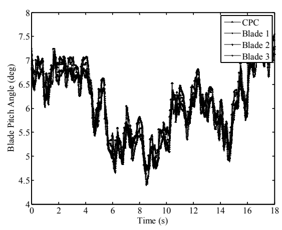
(d) The blade 1 flapwise moment



(e) The yaw moment on the rotor



(f) The tilt moment on the rotor



(g) The pitch angles of three blades

Fig.3. Control effect diagram using IPC underling turbulence wind

Conclusion

The simulation results show that the pitch controller with MSDWDP-IPC adjusts all blade pitch angle respectively by the dynamic weight coefficient distribution according to the location of the blade in the rotation plane. In the process of constant power control, the MSDWDP-IPC not only directly smoothes the wind turbine torque fluctuation, but also indirectly reduces the blade flapwise moment fluctuation, the yaw moment fluctuation and the tower tilt moment fluctuation on the tower. Thus, it reduces effectively the fatigue loads on the blade, the wind turbine main shaft, the drive train, the pitch bearing, the hub, the yaw bearing and the tower; increases the wind turbine mechanical life; and greatly reduces the maintenance costs and so on. Compared with CPC, the IPC will increase the action frequency of the pitch actuator mechanism, that it will put forward high requirements to the pitch actuator. This requires further study in the future.

Appendix

Wind Turbine Parameters:

Rated power = 2MW, Rated wind rotor speed = 21 r/min, wind rotor diameter = 80m, Hub radius = 1.5m, Hub height= 61.5m, Tower radius =1.75m, Rotor overhang = 3.7m, Rated wind speed = 9.9m/s, Cut in wind speed = 4m/s, Cut out wind speed=25m/s, Wind shear exponent = 0.2.

Acknowledgements

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