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Mitigation of Fatigue Loads Using Individual Pitch Control of Wind Turbines Based on FAST

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Abstract-**With the increase of wind turbine dimension and capacity, the wind turbine structures are subjected to prominent loads and fatigue which would reduce the lifetime of wind turbines. Individual pitch control (IPC) is used in this paper to attenuate the blade root bending moment and the tilt and yaw moments and fatigue. The loading transfer from rotational coordinate system to the fixed coordinate system of the wind turbine is analyzed. In order to make the simulation results more reliable, the wind turbine code FAST is applied to doubly fed induction generator (DFIG) based power system to demonstrate the correctness of individual pitch control strategy. The performance of the proposed control method is tested and compared with that using collective pitch control (CPC), demonstrating the effectiveness of individual pitch control of wind turbines.**

Index Terms-- **Blade loads, FAST, Individual pitch control, Wind turbine**

I. INTRODUCTION

During the last few decades, the appetite for energy in the world has been increasing at a tremendous rate, especially wind power generation has experienced an uninterrupted and accelerating growth and the trend is likely to continue. In order to enable even greater role of wind energy in power production it is necessary to increase the size and unit power of wind turbines [1].

With the increase of wind turbine capacity, rotor diameter, nacelle weight, tower height and the flexibility of wind turbine increase rapidly. Dynamic loads caused by the rotational sampling of turbulence, the tower shadow and the wind shear affect large scale wind turbine more and more prominently, which is an essential factor that must be considered.

To cope with such great loads massive structure would be needed which would increase wind turbine's price and also pose a limit to its further growth. Instead of massive structure to withstand the worst potential loads it is much more convenient to use intelligent control methods by which loads reduction can be achieved [2]. Therefore, control algorithms that can assure load and fatigue reduction become a necessity and also attractive.

As we know, the adjustment of pitch angle plays an important role in the output power of the wind turbine and the blade loads and fatigue. But the traditional collective pitch control strategies move the three blades synchronously for three bladed wind turbines [3]. However, aerodynamic forces on three blades are different, so the rotor of the wind turbine endures unbalanced load all the time [4].

Nowadays, many of the commercial turbines use individual pitch actuators anyway, the braking systems can be considered independent since with careful design, obviating the need for a high capacity shaft brake [5]. So the blade pitch angles of the wind turbine could be controlled individually, and this process is named individual pitch control with the added advantage that the failure probability of the system is significantly reduced even if one of the blade mechanisms fails [6]. How to coordinate the three blades to make the output power stable and attenuate the wind turbine loads is a research focus.

In this paper, individual pitch control is applied to doubly fed induction generator based wind power generation system to mitigate the blade loads and also the tilt and yaw moments on the fixed part of the wind turbine structure. Three different simulation packages, namely TurbSim [7], FAST [8], and Simulink are used to model the wind, mechanical and electrical aspects of the wind turbine and DFIG system in detail.

This paper is organized as follows. In Section 2 an overview of a DFIG based wind power system is given and the scheme of field oriented control of DFIG system is shown. Section 3 analyzes the structural loading of the wind turbine and the process of load transfer from the rotating part to the fixed part of the structure. Section 4 describes the purpose of individual pitch control approach and its control strategy is demonstrated. The performance of simulation results is presented in Section 5. Section 6 gives a summary of this paper.

II. DOUBLY FED INDUCTION GENERATOR BASED WIND POWER GENERATION SYSTEM
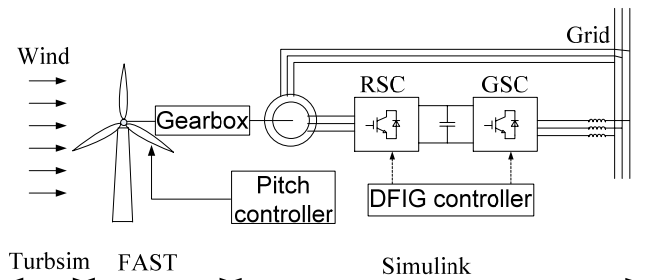

Fig. 1. The overall scheme of the DFIG wind power generation system

The schematic diagram of doubly-fed induction generator system is shown in Fig. 1. This system consists of a wind turbine, gearbox, doubly-fed induction generator, a back-to-back converter which is composed of rotor side converter (RSC) and grid side converter (GSC) and a dc-link capacitor as energy storage is placed between the two converters. These two converters have to handle only a fraction (20-30%) of the rated power, so the price of the system can be relatively cheap.

The stator winding of DFIG is directly connected to the power grid while the rotor winding is connected via slip rings to RSC. The control of generator torque, speed and the stator active and reactive power can be implemented by controlling the two converters and the pitch controller.

In this paper, three-dimensional turbulent wind has been simulated by TurbSim. Wind turbine code FAST has been used to simulate the mechanical parts of wind turbine and the drive train. The controllers, DFIG, and power system have been modeled by Simulink blocks.

A. TurbSim and FAST

TurbSim and FAST are developed at the National Renewable Energy Laboratory (NREL) and they are accessible to the public.

TurbSim is a stochastic, full-field, turbulent-wind simulator. It numerically simulates time series of three-dimensional wind velocity vectors at points in a vertical rectangular grid. TurbSim output can then be used as input into AeroDyn-based codes such as FAST, YawDyn, or MSC.ADAMS [7].

The open source code FAST can be used to model both two and three bladed, horizontal-axis wind turbines. It uses Blade Element Momentum (BEM) theory to calculate blade aerodynamic forces and uses an assumed approach to formulate the motion equations of the wind turbine. For three-bladed wind turbines, 24 DOFs (Degree of Freedoms) are used to describe the turbine dynamics. Their models include rigid parts and flexible parts. The rigid parts include earth, base plate, nacelle, generator, and hub. The flexible parts include blades, shaft, and tower. FAST runs significantly faster than a large comprehensive code such as ADAMS because of the use of the modal approach with fewer degrees of freedoms (DOFs) to describe the most important parts of turbine dynamics [9-10].

B. Control of the DFIG Connected to the Grid

The DFIG control in this paper uses field oriented control which has been widely used in many literatures. It's not the main point of this paper, so it just gives the control scheme of the DFIG connected to the grid, shown in Fig. 2. In this paper, one of the control objectives is to keep the output power, including the active power at its rated value and the reactive power at 0.
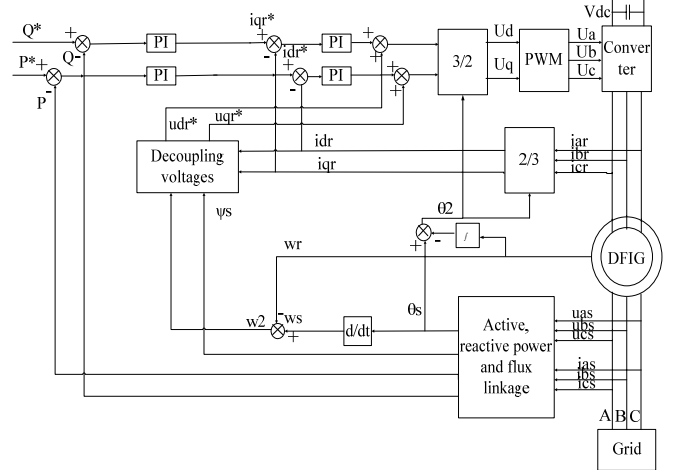

Fig. 2. Control scheme of DFIG based power system connected to the grid

III. WIND TURBINE STRUCTURAL LOADS

Loads upon the wind turbine structure arise from several factors [9]. The main cause of the wind turbine structural loading is the fact that only a portion of the wind power can be transformed into the driving torque of the wind turbine rotor while large amount of it is transformed into the rotor thrust that will increase prominently with the increase of the wind speed and the wind turbine dimension.

The sources of the structural loadings are also due to stochastic process and to periodic processes. The stochastic process is referred to as turbulence that determines wind speed at different times and heights. These periodic processes are due largely to two effects termed wind shear and tower shadow. Wind shear is used to describe the variation of wind speed with height while tower shadow describes the reduction of wind speed due to the tower structure [11].

For a three bladed wind turbine, since the three blades are at different positions and under turbulent and periodic wind field, they are subjected to periodic blade loadings with oscillating magnitude which are very undesirable since they cause oscillatory stress on the structure which are responsible for a significant contribution to fatigue loads.

In order to calculate loadings on the elements of the fixed part of the structure, it is first necessary to transform the loads defined in terms of rotating axis system into the hub loads expressed in terms of a fixed axis system, since the blade root bending moments are the source of the loads on the fixed part of the structure.

The rotational frame of reference of each blade can be seen in Fig. 3 (a). Therefore, if three-bladed rotor without any asymmetry is assumed, the blade root bending moments of the second and the third blade will be 120° out of phase in respect to the first blade.

The fixed hub frame of reference is shown in Fig. 3 (b), and the origin is defined in the center of hub. The loads on the fixed part of the wind turbine structure can be projected from the blade bending moments of the rotational frame of reference.

(a) Blade frame of reference (rotational frame of reference)

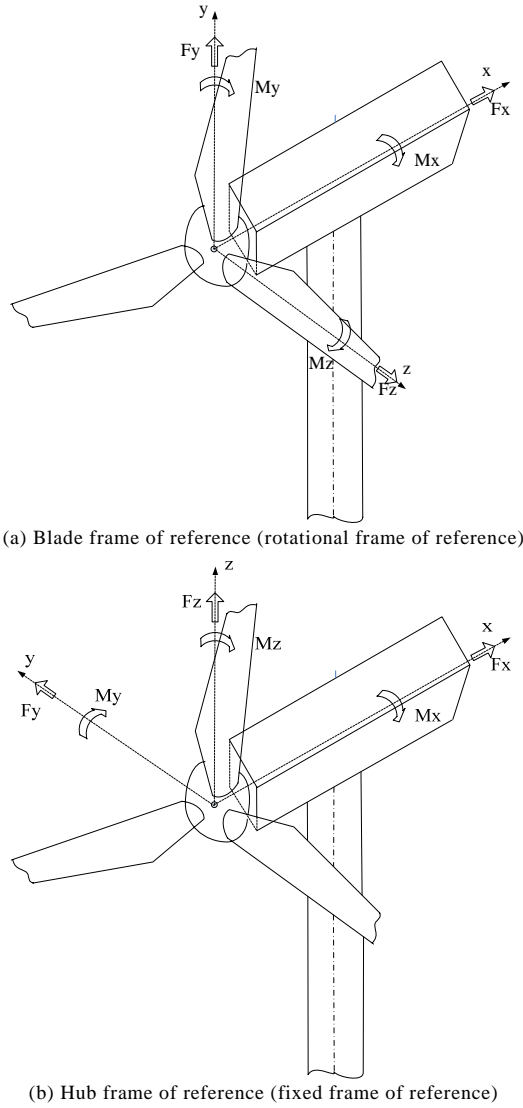(b) Hub frame of reference (fixed frame of reference)

Fig.3 Frames of reference for definition of loads upon the blade root and the fixed part of the structure [12]

This loading transformation from blade frame of reference to hub frame of reference results in the loads on the fixed part of the wind turbine structure in two main axes y and z that are usually referred to as tilt and yaw loads:

$$\begin{bmatrix} M_{tilt} \\ M_{yaw} \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & \cos(\omega t + \frac{2\pi}{3}) & \cos(\omega t + \frac{4\pi}{3}) \\ \sin(\omega t) & \sin(\omega t + \frac{2\pi}{3}) & \sin(\omega t + \frac{4\pi}{3}) \end{bmatrix} \begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix} \quad (1)$$

where $M_{1,2,3}$ stand for blade root bending moment. As mentioned above, the blades are exposed to different wind speeds when rotating because of turbulence and tower shadow and wind shear effects around the rotor disc. It could result in oscillations in blade structural loads where the most significant is the first harmonic on frequency equal to the wind turbine rotor frequency ($1p$ - once per revolution), together with harmonics of this frequency, i.e. $2p$, $3p$, $4p$ and so on.

When tilt and yaw moments are considered by Park's

transformation, mean value of load as well as loads of frequency $3 \cdot i \cdot \omega$, i = 1,2,3… are removed from the transformed signal. Other harmonics are transferred to the nearest harmonic that is multiplier of the frequency $3p$. So the hub and the rest of the structure will experience the harmonics at $3p$, $6p$, etc., For example, $3p$ and $6p$ signal contents in the fixed frame of reference appear as $2p$, $4p$, $5p$ and $7p$ signal contents in the rotational frame of reference.

IV. INDIVIDUAL PITCH CONTROL

The individual pitch control scheme is illustrated in Fig. 4 [13].

The blade root bending moments are detected through load sensors or by estimation without sensors [1]. Then the three blade root bending moment signals are transformed into two orthogonal d- and q-axes which stand for tilt and yaw moments by means of Park's transformation.

The d,q-axes controllers generate pitch demands respectively for each axis, and the two d- and q-axis pitch demands are converted by the reverse transformation to give three pitch demand increments for each blade. These are each summed with the collective pitch demand to give a total pitch demand for each blade.

A. 1p blade root bending moment mitigation

The block d,q-axes transformation describes Park's transformation which can be expressed as:

$$\begin{bmatrix} M_d \\ M_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\omega t) & \cos(\omega t + \frac{2\pi}{3}) & \cos(\omega t + \frac{4\pi}{3}) \\ \sin(\omega t) & \sin(\omega t + \frac{2\pi}{3}) & \sin(\omega t + \frac{4\pi}{3}) \end{bmatrix} \begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix} \quad (2)$$

As mentioned above, the fatigue on the blade is mainly caused by the $1 p$ load component in the rotational coordinate system, which turns out to be $0p$ (mean value) in the d,q- axes. In order to mitigate the $1p$ blade root bending moment, the low-pass filter is added in series with the PI controller in the fixed coordinate system to avoid the higher frequency ($3p$, $6p$, etc.) effect, as can be seen in Fig. 5. The cut-off frequency of the low-pass filter is smaller than the $3p$ frequency.

After getting the pitch angle demand increments for d,q-axes, they are converted to the increments for the three blade pitch angles by the inverse Park's transformation, denoted by inverse d,q-axes transformation that can be calculated as:

$$\begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & \sin(\omega t) \\ \cos(\omega t + \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\ \cos(\omega t + \frac{4\pi}{3}) & \sin(\omega t + \frac{4\pi}{3}) \end{bmatrix} \begin{bmatrix} \beta_d \\ \beta_q \end{bmatrix} \quad (3)$$

where $\beta_{d,q}$ are the pitch angle demand increments for d,q-axes, and $\beta_{1,2,3}$ are the three pitch angle demand increments for each blade respectively.
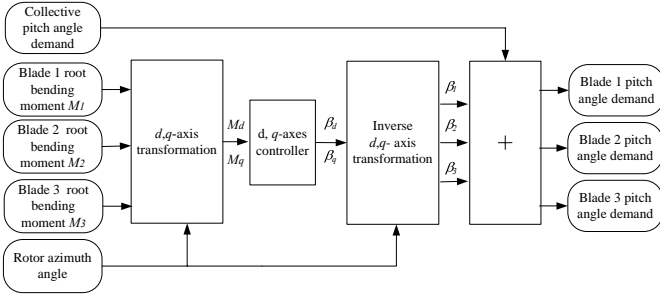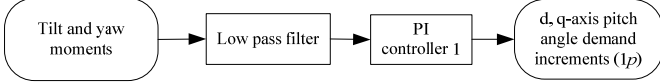
Fig. 4. Individual pitch control principle scheme

Fig. 5. The controller for d,q- axes

B. 3p tilt and yaw moments mitigation

The fatigue in the tilt and yaw moments mainly arise from the 3p oscillation of the loads on the fixed part of structure which is from the 2p and 4p blade root bending moments in the rotational frame of reference. So the 3p load reduction on the fixed part can be achieved via 2p and 4p blade root bending moment reduction.

The same approach for 1p load reduction can be applied to mitigate the 2p and 4p blade loads. Take 2p load reduction for example. M_{d2} and M_{q2} of which the 2p load component turns out to be the mean value can be derived by using (4). Subsequently the same low pass filter and the same PI controller as in Fig. 5 are adopted. The outputs of the PI controllers are β_{d2} and β_{q2} that account for the pitch angle increments for d,q-axes. Through the inverse Park's transformation (5), the increments for three pitch blade angles $\beta_{2p1,2,3}$ are obtained.

$$\begin{bmatrix} M_{d2} \\ M_{q2} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(-2\omega t) & \cos(-2\omega t + \frac{2\pi}{3}) & \cos(-2\omega t + \frac{4\pi}{3}) \\ \sin(-2\omega t) & \sin(-2\omega t + \frac{2\pi}{3}) & \sin(-2\omega t + \frac{4\pi}{3}) \end{bmatrix} \begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} \beta_{2p1} \\ \beta_{2p2} \\ \beta_{2p3} \end{bmatrix} = \begin{bmatrix} \cos(-2\omega t) & \sin(-2\omega t) \\ \cos(-2\omega t + \frac{2\pi}{3}) & \sin(-2\omega t + \frac{2\pi}{3}) \\ \cos(-2\omega t + \frac{4\pi}{3}) & \sin(-2\omega t + \frac{4\pi}{3}) \end{bmatrix} \begin{bmatrix} \beta_{d2} \\ \beta_{q2} \end{bmatrix} \quad (5)$$

Similar method can be used for 4p blade load reduction. This approach can also be used to attenuate the higher frequency loads (6p, 9p, etc.) on the fixed part of the structure. The reference value to 0p and 3p for each load controller in d,q- system is 0, in this way it can stabilize the blade root bending moment and tilt and yaw moments at their mean values.

So now the d,q-axes pitch angle demand comprises two components: one pitch to mitigate the 1p frequency blade root bending moment, and the other one is to reduce the 3p loads on the fixed part of structure.

V. SIMULATION RESULTS

Doubly fed induction generator	
Rated capacity (MW)	1.5
Rated stator voltage(V)	690
Rated frequency(Hz)	50
Stator resistance(pu)	0.022
Rotor resistance(pu)	0.026
Stator leakage inductance(pu)	0.177
Rotor leakage inductance(pu)	0.116
Magnetizing inductance	4.68
Number of pole pairs	2
Lumped inertia constant(s)	3.0
Wind turbine	
Blade radius(m)	35
Number of blades	3
Cut-in/cut-out wind speed(m/s)	3/25
Gearbox ratio	81
Hub height(m)	82
Rated power(MW)	1.5
Pitch controller	
Max/min pitch angle	45/0 degree

To verify the effectiveness of proposed individual pitch control, some results are obtained from simulations. The wind turbine code FAST which could be relatively convincing is used. The parameters of the wind turbine and generator are given in Table 1.
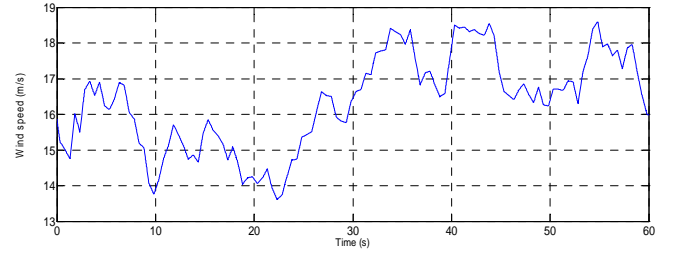

Fig. 6. Wind speed with mean value of 15m/s

Fig. 6 shows the stochastic wind generated by TurbSim with mean speed of 15 m/s. Under this condition, the pitch controller should be used to keep the generator output power at the rated value.
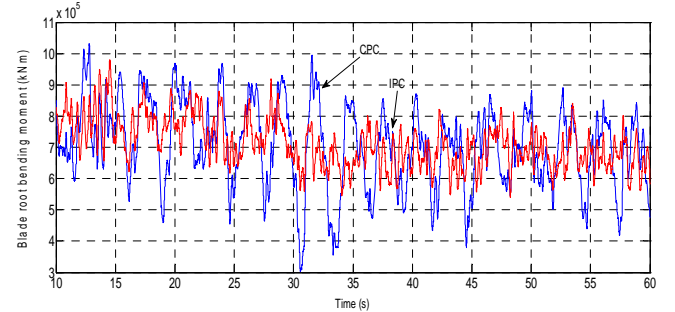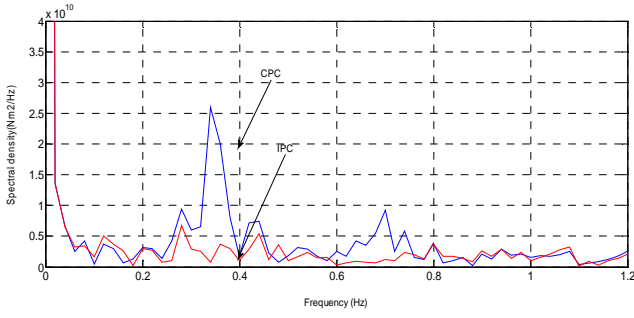

Fig. 7. Blade root bending moment

Fig. 8. Spectrum of Blade root bending moment

Fig. 7 demonstrates the blade root bending moments with CPC and IPC and the waveform in Fig. 8 is the spectrum density of blade root bending moment. Obviously the blade root bending moment oscillates in a much smaller range, and the fatigue caused by $1p$ is mitigated prominently with IPC.
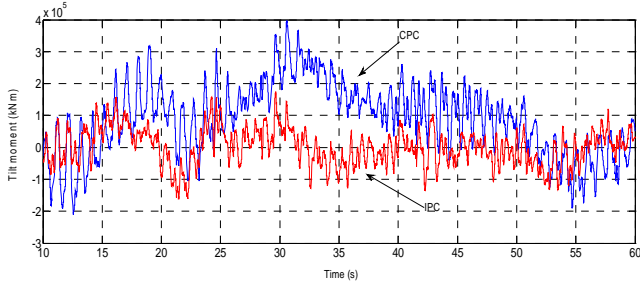

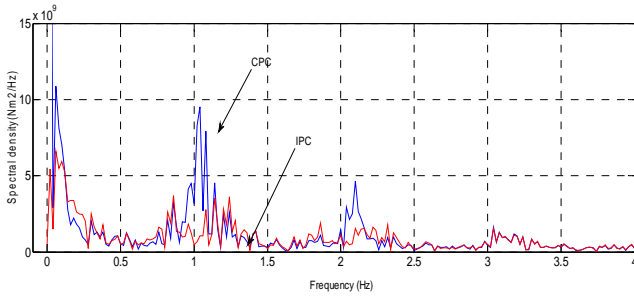Fig. 9. Tilt moment of the hub

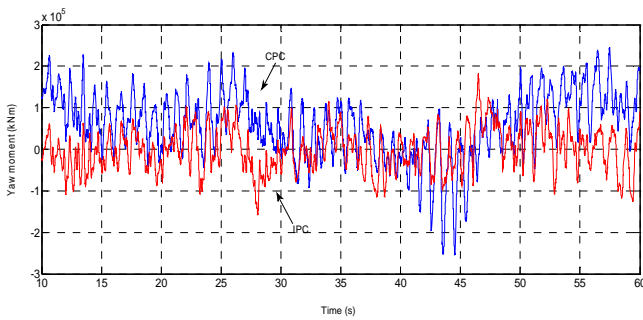Fig. 10. Spectrum of the tilt moment
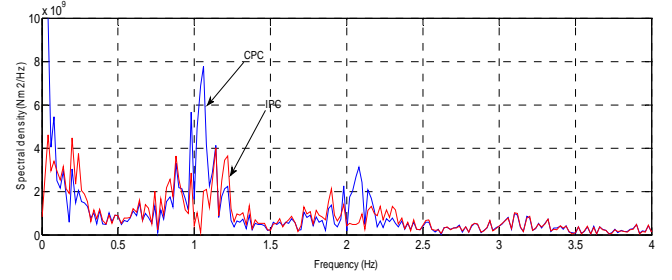

Fig. 11. Yaw moment of the hub

Fig. 12. Spectrum of the yaw moment

Also Fig. 9 and Fig. 11 illustrate the tilt and yaw moments of the hub with CPC and IPC, and Fig. 10 and Fig. 12 are their spectrum density waveforms respectively. It is notable that the mean values of the tilt and yaw moments almost disappear due to the fact that the $1p$ loading in the blade root bending moment which is the source of tilt and yaw moments is much reduced by individual pitch control. The $3p$ loading which is the main fatigue source on the fixed structure is also attenuated as well as the $6p$ loading. From these figures, it is proven that the proposed individual pitch control strategy is able to reduce the fatigue loads on the blade and the hub, which might increase the lifetime of the turbine.
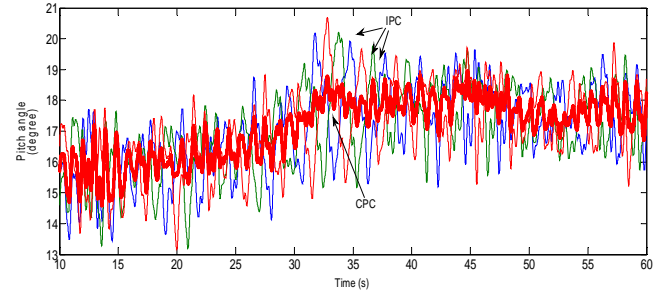

Fig. 13. Blade pitch angle

The blade pitch angle waveforms with CPC and IPC are shown in Fig. 13. In CPC system, the three blades are controller with the same pitch angle, which cannot change the blade loads effectively according to different conditions. But in IPC system, the blade pitch angles can be adjusted independently, as can be seen in Fig. 13. It is important to point out that the response of the pitch actuator is crucial in achieving load reductions of this scale.
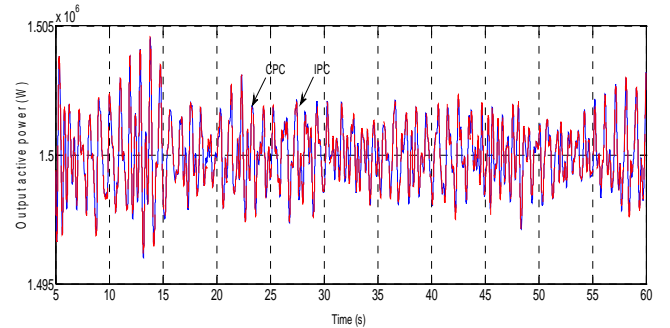

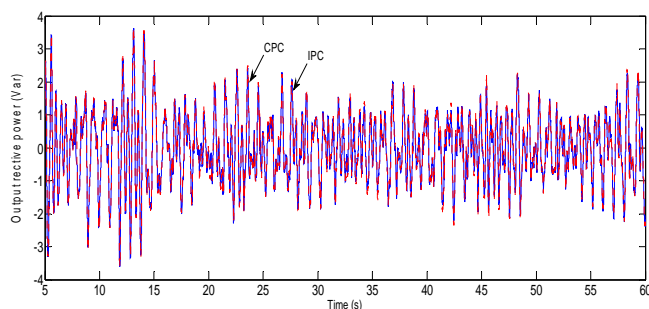Fig. 14. Output active power of DFIG with CPC and IPC

Fig. 15. Output reactive power of DFIG with CPC and IPC

Fig. 14 and Fig. 15 give the output active and reactive power generated by DFIG with CPC and IPC respectively. With IPC approach it can also keep the output active power at the rated value and the reactive power minimum.

VI. CONCLUSION

Individual pitch control is applied to DFIG based wind power system in this paper. It demonstrates a relatively straightforward approach of individual pitch control algorithm capable of attenuating the dominant fatigue loads on the blade(1p) and on the fixed components (3p), resulting in significant fatigue load reductions on the whole wind turbine. The individual pitch control process is tested with FAST and Simulink, demonstrating the effectiveness of the proposed control strategy.

Developments of control strategies to tackle problems such as tower vibration and drive train oscillation, and loads reduction under grid fault conditions are subjects of ongoing and future work.

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