Individual Pitch Control for Mitigation of Power Fluctuation of Variable Speed Wind Turbines

Zhang, Yunqian; Hu, Weihao; Chen, Zhe; Cheng, Ming

Published in:
Proceedings of the 10th International Power and Energy Conference

DOI (link to publication from Publisher):
10.1109/ASSCC.2012.6523343

Publication date:
2012

Document Version
Early version, also known as pre-print

Individual Pitch Control for Mitigation of Power Fluctuation of Variable Speed Wind Turbines

Yunqian Zhang Weihao Hu Zhe Chen
Department of Energy Technology
Aalborg University
Aalborg, Denmark
yqz@et.aau.dk; whu@et.aau.dk; zch@et.aau.dk

Ming Cheng
School of Electrical Engineering
Southeast University
Nanjing, China
mcheng@seu.edu.cn

***Abstract*— Grid connected wind turbines are the sources of power fluctuations during continuous operation due to wind speed variation, wind shear and tower shadow effects. This paper presents an individual pitch control (IPC) strategy to mitigate the wind turbine power fluctuation at both above and below the rated wind speed conditions. Three pitch angles are adjusted separately according to the generator output power and the azimuth angle of the wind turbine. The IPC strategy scheme is proposed and the individual pitch controller is designed. The simulations are performed on the NREL (National Renewable Energy Laboratory) 1.5MW upwind reference wind turbine model. The simulation results are presented and discussed to show the validity of the proposed control method.**

Keywords-wind turbine; IPC; power fluctuation; FAST

I. INTRODUCTION

During the last few decades, with the growing concerns about environmental pollution and energy shortage, great efforts have been taken around the world to implement renewable energy projects. With advanced techniques, cost reduction and low environmental impact, wind energy is certain to play an important role in the world's energy [1]. With the capacity increase of the wind turbines, wind power penetration into the grid increases dramatically and the power quality becomes an important issue.

Grid connected variable speed wind turbines are fluctuating power sources during continuous operation. The power fluctuation is normally referred to as the 3p oscillations which are caused by wind speed variation, wind shear and tower shadow effects. As a consequence, the wind turbine aerodynamic power will drop three times per revolution for a three-bladed wind turbine.

Several methods have been proposed for the mitigation of wind power fluctuations of grid connected wind turbines in some literatures. Reactive power compensation is the most commonly used technique, however, this method shows its limits, when the grid impedance angle is low in some distribution networks [2]. Also active power control by varying the DC-link voltage of the back to back converter is presented to attenuate the power fluctuation [3]. But a big DC-link capacitor is required in the method due to the storage of the fluctuation power in the DC-link. These papers use compensation or absorption methods to reduce the power oscillations, which have not solved the problem from the source part of wind turbine system for the power fluctuations.

In this paper, an individual pitch control scheme is proposed for mitigation of power oscillations of wind turbine system. It can attenuate the power fluctuation by adjusting three pitch angles separately. The power oscillations due to 3p effects are attenuated by pitch angles adjustment according to the output power feedback and the azimuth angle, such that the output power of the generator is smoothed prominently. The FAST (Fatigue, Aerodynamics, Structures, and Turbulence) code which is qualified to simulate the complexity of three-bladed wind turbines is adopted in the simulation. The individual pitch control scheme is presented and the validity of the proposed method is verified by the simulation results.

This paper is organized as follows. In Section 2 the power fluctuation source, namely, wind shear and tower shadow are introduced, and the aerodynamic torque considering the 3p effects is described. Section 3 demonstrates an overview of a DFIG based wind power system and each part is briefly described. Section 4 proposes the individual pitch control scheme, and the control principle is presented at both high and low wind speed conditions. The individual pitch controller is then designed. The performance of simulation results is presented in Section 5. Section 6 gives a summary of this paper.

II. POWER FLUCTUATION ANALYSIS

Power generated by wind turbines is much more variable than that produced by conventional generators. The power fluctuations are due both to stochastic processes that determine wind speed at different times, and to periodic processes that are referred to as wind shear and tower shadow. Wind shear is used to describe the variation of wind speed with height while tower shadow describes the redirection of wind due to the tower structure [4].

A. Wind shear

The increase of wind speed with height is known as wind shear. A common wind shear model, shown as (1), is taken directly from the literature on wind turbine dynamics [4]

$$V(z) = V_H \left(\frac{z}{H}\right)^{\alpha} \tag{1}$$

where V_H is the wind speed at hub height, H is elevation of rotor hub and z is elevation above ground, α is the empirical wind shear exponent and its value increases with the surface roughness.

B. Tower shadow

Today most wind turbines are constructed with a rotor upwind of the tower to reduce the tower interference of the wind flow. In the upwind rotor case, the wind speed V_{tow} considering tower shadow effect can be modeled using potential flow theory [4].

$$v_{tow} = V_H + V_0 a^2 \frac{y^2 - x^2}{(x^2 + y^2)^2} \tag{2}$$

where a is the tower radius, and x and y are the components of the distance from each blade to the tower center in the lateral and the longitudinal directions, respectively. V_0 is the spatial mean wind speed, and $V_0 = (1 + \alpha(\alpha - 1)R^2 / (8H^2))V_H$, where R is the wind turbine rotor radius.

C. Total aerodynamic torque

When wind shear and tower shadow effects are taken into account, the aerodynamic torque of the wind turbine contains a component with frequency 3p, which means the aerodynamic torque will drop three times per revolution. Fig. 1 illustrates the overall wind turbine aerodynamic torque, which obviously shows the 3p effect, and also the aerodynamic torque has the maximum drop when one of the three blades is directly in front of the tower.

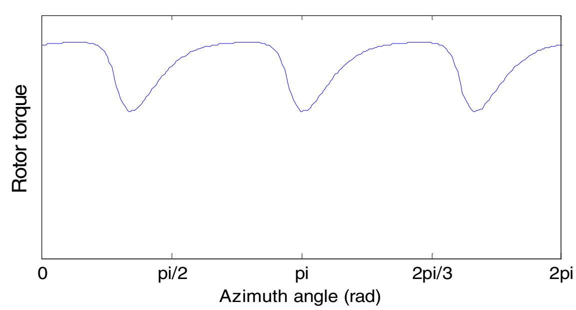

Figure 1. Aerodynamic torque involving 3p effects

III. SYSTEM CONFIGURATION

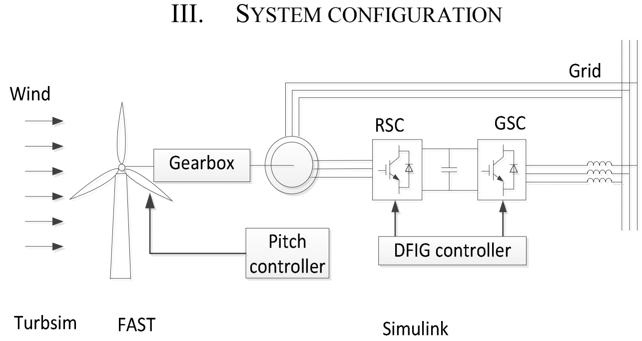

Figure 2. The overall scheme of the DFIG based wind turbine system

The overall scheme of DFIG based wind turbine system is shown in Fig 2, which consists of a wind turbine, gearbox, DFIG, 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 placed between the two converters. In this paper, turbulent wind is simulated by TurbSim. Wind turbine code FAST is used to simulate the mechanical parts of wind turbine and the drivetrain. The pitch and converter controllers, DFIG, and power system are modeled by Simulink blocks.

A. TurbSim and FAST

TurbSim and FAST are developed at the National Renewable Energy Laboratory (NREL) and they are accessible and free 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 FAST [5]. 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.

B. Mechanical Drivetrain

In order to take into account the effects of the generator and drivetrain to the wind turbine, two-mass model is used which is suitable for transient stability analysis [6] shown in Fig. 3. The drivetrain modeling is implemented in FAST, and all values are cast on the wind turbine side.

The equations for modeling the drivetrain are given by:

$$J_w \frac{d^2\theta_w}{dt^2} = T_w - D\left(\frac{d\theta_w}{dt} - \frac{d\theta_g}{dt}\right) - K(\theta_w - \theta_g) \tag{3}$$

$$J_g \frac{d^2\theta_g}{dt^2} = D\left(\frac{d\theta_w}{dt} - \frac{d\theta_g}{dt}\right) + K(\theta_w - \theta_g) - T_e \tag{4}$$

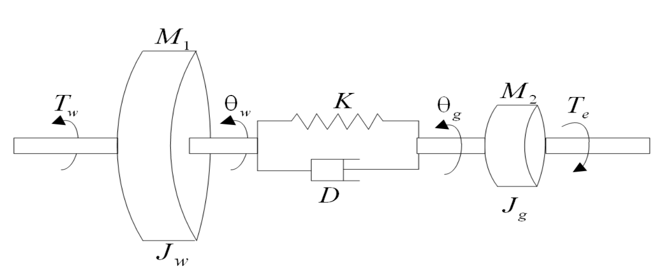

Figure 3. Two-mass model of the drivetrain

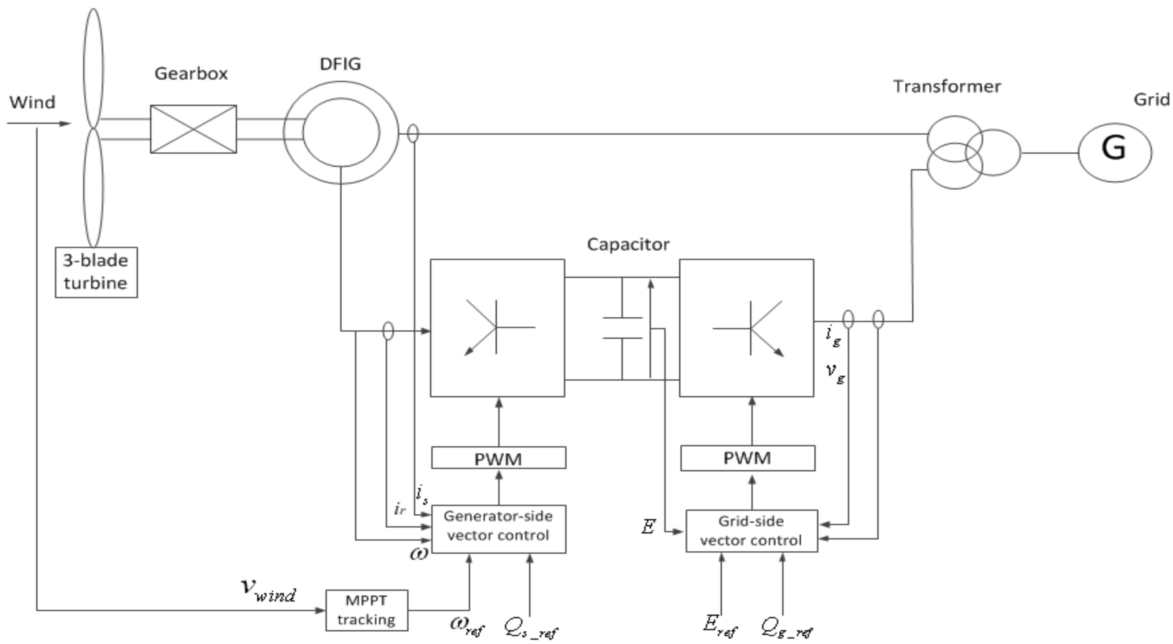

Figure 4. Control diagram of RSC and GSC of grid-connected wind turbine with DFIG

where *Jw*, *Jg* are the moment of inertia of wind turbine and generator respectively, *Tw*, *Te* are the wind turbine torque and generator electromagnetic torque respectively, θw, θg are the mechanical angle of wind turbine and generator, *K* is the drivetrain torsional spring, *D* is the drivetrain torsional damper.

C. *DFIG model and converters control*

The model of the DFIG in Simulink is based on *d-q* equivalent model. All electrical variables are referred to the stator.

Vector control techniques are the most commonly used methods for back to back converters in wind turbine system. Two vector control schemes are illustrated respectively for the RSC and GSC, as shown in Fig. 4. Normally the control objective of RSC is to implement maximum power tracking by controlling the electrical torque of DFIG, while the objective of GSC is to keep the DC-link voltage constant. Usually the values of reactive power of RSC and GSC are set to zero to ensure unity power factor operation and reduce the current of RSC and GSC. It's not the main point of this paper, so the details of the converter control will not be described.

IV. INDIVIDUAL PITCH CONTROL FOR MITIGATION OF WIND TURBINE POWER FLUCTUATION

As illustrated in Fig. 1, the aerodynamic torque will drop three times per revolution, so that the aerodynamic power of the wind turbine as well as the generator output power will also drop three times in a cycle. If the aerodynamic torque can be controlled well to some extent that it will not drop or not drop so prominently when one of the blades is directly in front of the tower, the wind turbine aerodynamic power thus the generator output power will fluctuate in a much smaller range.

When wind speed is above rated wind speed, pitch angle should be tuned by traditional collective pitch control (CPC) to keep the output power at its rated value in order not to overload the system, and normally the 3p effect is not taken into account. For attenuating the power oscillation caused by 3p effect, one of the blade pitch angles can be added by a small pitch increment which is dependent on the wind turbine azimuth angle and the generator output power.

When wind speed is below the rated wind speed, usually the control objective of wind turbine is to implement maximum power tracking by generator electrical torque control. Pitch control is not used in this area. However if the pitch angles can be adjusted around a small average value, the 3p effect can also be reduced. For this purpose, the pitch angle should leave a small amount of residual for pitch movement. This means part of the wind energy will be lost.

Based on this control concept, a novel individual pitch control strategy is proposed. The control scheme is shown in Fig. 5. The control scheme consists of two control loops: collective pitch control loop and individual pitch control loop.

The collective pitch control is responsible for limiting the output power. In this loop, P_{gref} is the rated generator power, P_g is the generator output power, β is the collective pitch angle, of which the minimum value β_{min} can be obtained by simulations under different wind speeds such that power fluctuation mitigation may compromise the power loss.

In the individual pitch control loop, the BPF (band pass filter) is to let the frequency of 3p generator active power through and block all other frequencies. P_{g3p} is the 3p component of the generator power, and this component will be sent to the signal processing (SP) block, due to the fact that the power signal has to be transferred to the pitch signal. The SP block can be represented as follows:

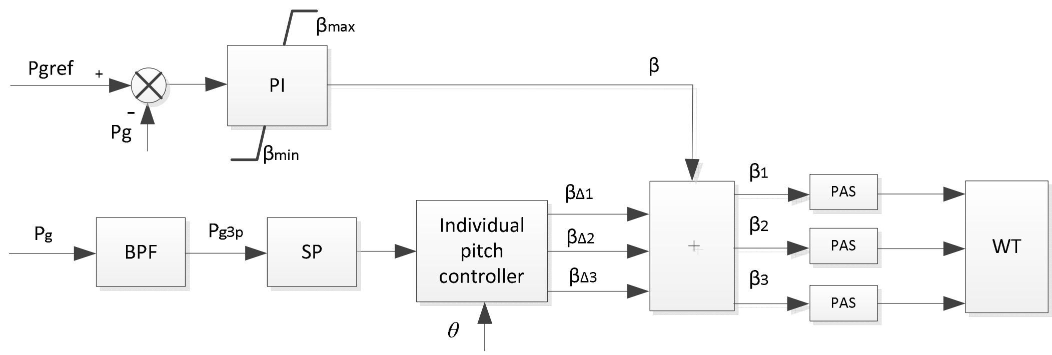

Figure 5. A novel individual pitch control scheme

$$F_{sp}(s) = \frac{K_{sp}}{T_{sp}s+1} \tag{5}$$

The individual pitch controller will output the three pitch increments $\beta_{\Delta 1,\Delta 2,\Delta 3}$ based on the 3p component of the generator active power and the azimuth angle θ.

In this paper, the wind turbine is simulated by FAST, in which blade 3 is ahead of blade 2, which is ahead of blade 1, so that the order of blades passing through a given azimuth is 3-2-1-repeat. The individual pitch controller will output a pitch increment signal which will be added to the collective pitch angle for a specific blade, dependent on the blade azimuth angle. The principle of the individual pitch controller is described in Table 1.

TABLE I. CONTROL PRINCIPLE OF INDIVIDUAL PITCH CONTROLLER

Azimuth angle θ	$\beta_{\Delta i}$
$0< \theta <2\pi/3$	$\beta_{\Delta 2}$
$4\pi/3> \theta >2\pi/3$	$\beta_{\Delta 1}$
$2\pi> \theta >4\pi/3$	$\beta_{\Delta 3}$

The three pitch increments will be each summed with the collective pitch angle to give a total pitch angle demand for each blade. The three pitch angle signals will be sent to the pitch actuation systems (PAS) to adjust the pitch angles along their longitudinal axes. The PAS can be represented using a first order transfer function:

$$F(s) = \frac{1}{T_{pas}s+1} \tag{6}$$

where T_{pas} is the time constant of the PAS.

V. SIMULATION RESULTS

In order to verify the validity of the proposed individual pitch control strategy, the whole wind turbine system is built in Simulink, and some simulation results are obtained under both high and low wind speeds. The parameters of DFIG and NREL 1.5 MW wind turbine are shown in Table 2.

TABLE II. PARAMETERS OF DFIG AND WIND TURBINE

DFIG and Wind turbine	
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
Blade radius(m)	35
Number of blades	3
Cut-in/cut-out wind speed(m/s)	3/25
Gearbox ratio	81
Drivetrain torsional spring (Nm/rad)	5.6e9
Drivetrain torsional damper (Nm/s)	1.0e7
Hub height(m)	82
Rated power (MW) of wind turbine	1.5
Max/min pitch angle (degree)	45/0
Max pitch rate (degree/s)	10
Time constant of PAS	0.1

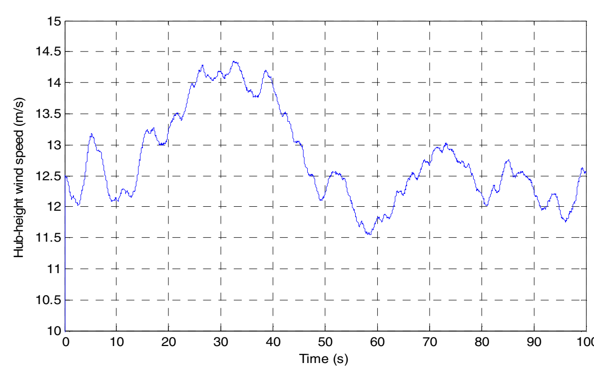

Figure 6. High wind speed

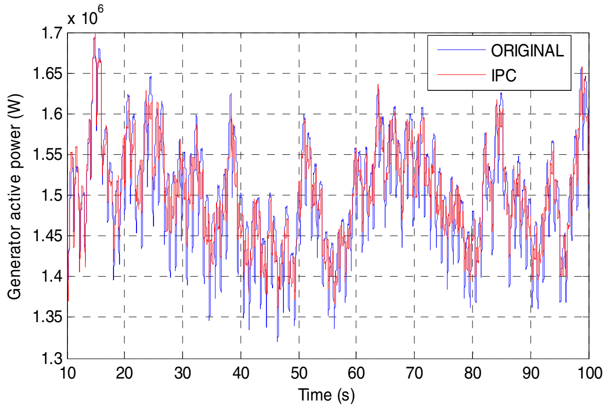

Figure 7. Generator output power (long time)

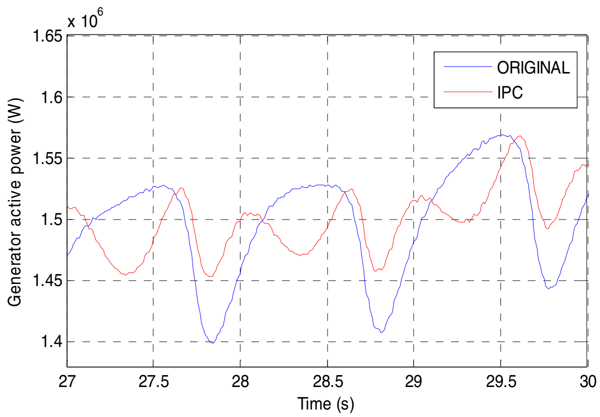

Figure 8. Generator output power (short time)

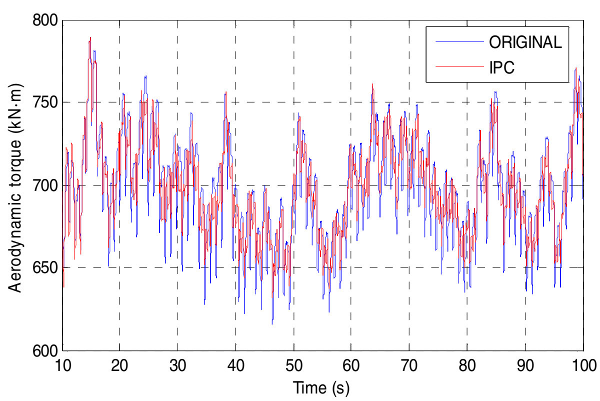

Figure 9. Aerodynamic torque

Fig. 6 shows the stochastic hub-height high wind with mean speed of 13m/s. Fig. 7 shows the generator output power during a long time range and for better comparison, the power waveform in a short time period is given in Fig. 8, from which it is shown the power oscillation is prominently reduced by individual pitch control. Fig. 9 is the aerodynamic torque of the wind turbine, demonstrating the validity of the proposed control method. Fig. 10 describes the individual pitch angles, which are tuned separately for the mitigation of power oscillation.

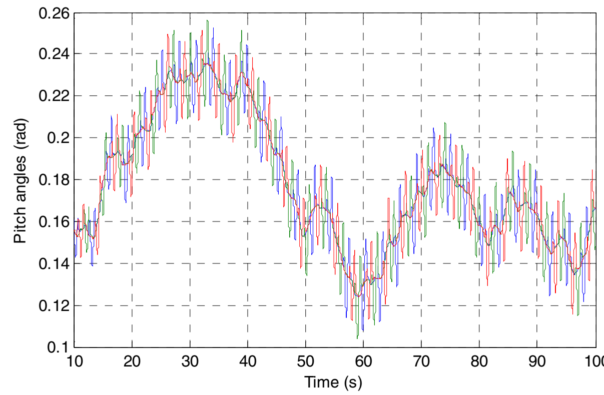

Figure 10. Individual pitch angles

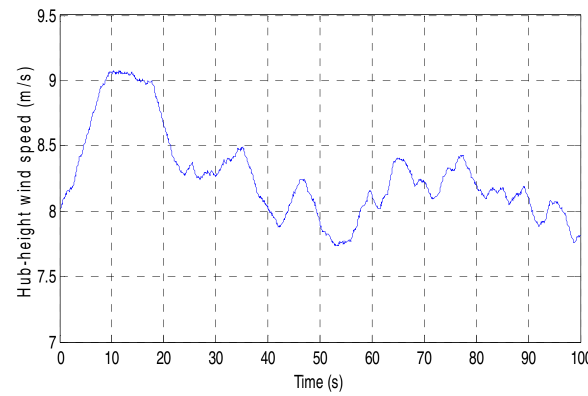

Figure 11. Low wind speed

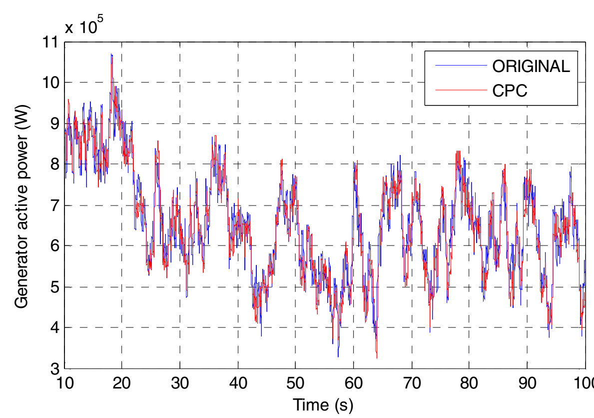

Figure 12. Generator output power

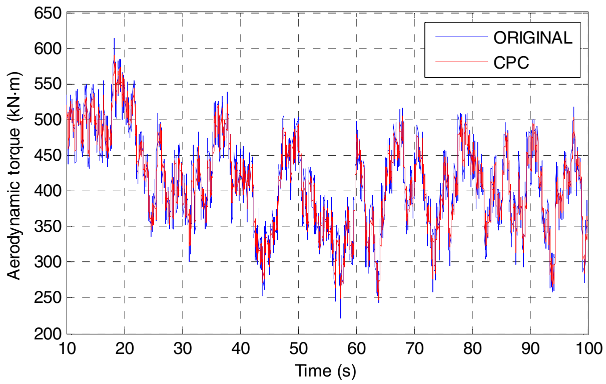

Figure 13. Aerodynamic torque

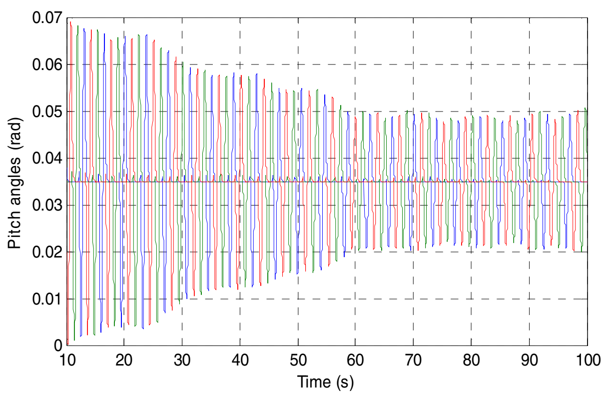

Figure 14. Individual pitch angles

Similar simulation results can be obtained under low wind speed. Fig. 11 shows the low wind speed with mean value of 8m/s. Fig. 12 and Fig. 13 are the generator output active power and aerodynamic torque respectively, illustrating that the fluctuations are not as much as those using the original method. Fig. 14 shows the pitch angles which are fluctuating in a small range to mitigate the power oscillations.

VI. Conclusion

The MW-level DFIG based variable speed wind turbine system is simulated using Simulink, Turbsim and FAST. A novel individual pitch control method is proposed to mitigate the wind turbine power fluctuation caused by wind shear and tower shadow effects. The individual pitch control scheme is presented and controller is designed. The simulations are performed on the NREL 1.5MW upwind reference wind turbine model. The simulation results demonstrate the capability of the proposed strategy.

References

[1] B. Chitti Babu, K.B. Mohanty, C. Poongothai, Performance of Double-Output Induction Generator for Wind Energy Conversion Systems, Proc. of IEEE First International Conference on Emerging Trends in Engineering and Technology, 2008, pp.933-938.

[2] T. Sun, Z. Chen, and F. Blaabjerg, "Flicker study on variable speed wind turbines with doubly fed induction generators," IEEE Trans. Energy Conversion, vol. 20, no. 4, pp. 896–905, Dec. 2005.

[3] W. Hu, Z. Chen, Y. Wang, and Z. Wang, "Flicker mitigation by active power control of variable-speed wind turbines with full-scale back-to-back power converters," IEEE Trans. Energy Conversion, vol. 24, pp. 640–649, Sep. 2009.

[4] D. S. L. Dolan, and P. W. Lehn, "Simulation model of wind turbine 3p torque oscillations due to wind shear and tower shadow," IEEE Trans. Energy Convers., vol. 21, no. 3, pp. 717–724, Sep. 2006.

[5] B. J. Jonkman, and M. L. J. Buhl. FAST User's Guide. National Renewable Energy Laboratory (NREL), Golden, CO, Tech. Rep. NREL/EL-500-38230, [Online]. Available: http://wind.nrel.gov/designcodes/simulators/fast/

[6] S. M. Muyeen, Md. Hasan, R. Takahashi, T. Murata, J. Tamura, Y. Tomaki, A. Sakahara, E. Sasano, "Comparative study on transient stability analysis of wind turbine generator system using different drive train models," IET Renewable Power Generation, 2007, 1, (2), pp. 131-141.