Implementation of Individual Pitch Control Technique on Variable Speed Wind Turbines with DFIG for Flicker Mitigation

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Abstract- *Due to the wind speed variation, wind shear and tower shadow effects, grid connected wind turbines are the sources of power fluctuations which may produce flicker during continuous operation. This project presents a model of an MW level variable speed wind turbine with a doubly fed induction generator to investigate the flicker emission and mitigation issues. An individual pitch control (IPC) strategy is proposed to reduce the flicker emission at different wind speed conditions. In this paper, the IPC scheme is proposed and the individual pitch controller is designed according to the generator active power and the azimuth angle of the wind turbine. 1.5-MW upwind reference wind turbine model Simulation results show that damping the generator active power by IPC is an effective means for flicker mitigation of variable speed wind turbines during continuous operation*.

Keywords: *- Flicker mitigation, IPC Scheme, wind turbine*

I. INTRODUCTION

In the last few decades, energy shortage and environmental pollution concerns had been increased significantly; great efforts have been taken around the world to implement renewable energy projects, especially wind power projects. With the increase of wind power penetration into the grid, the power quality becomes an important issue. One important aspect of power quality is flicker since it could become a limiting factor for integrating wind turbines into weak grids, and even into relatively strong grids if the wind power penetration levels are high.

Flicker is defined as “an impression of unsteadiness of visual sensation induced by a light stimulus, whose luminance or spectral distribution fluctuates with time”. Flicker is induced by voltage fluctuations, which are caused by load flow changes in the grid. Grid-connected variable speed wind turbines are fluctuating power sources during continuous operation. The power fluctuations caused by wind speed variation, wind shear, tower shadow, yaw errors, etc., lead to the voltage fluctuations in the network, which may produce flicker. Apart from the wind power source conditions, the power system characteristics also have impact on flicker emission of grid-connected wind turbines, such as short-circuit capacity and grid impedance angle.

The flicker emission with different types of wind turbines is quite different. Though variable-speed wind turbines have better performance with regard to the flicker emission than fixed-speed wind turbines, with the large increase of wind power penetration level, the flicker study on variable speed wind turbines becomes necessary and imperative.

A number of solutions have been presented to mitigate the flicker emission of grid-connected wind turbines. The most commonly adopted technique is the reactive power compensation. However, the flicker mitigation technique shows its limits in some distribution networks where the grid impedance angle is low. When the wind speed is high and the grid impedance angle is 10◦, the reactive power needed for flicker mitigation is 3.26 per unit. It is difficult for a grid-side converter (GSC) to generate this amount of reactive power, especially for the doubly fed induction generator (DFIG) system, of which the converter capacity is only around 0.3 per unit. The STATCOM which receives much attention is also adopted to reduce flicker emission.

However, it is unlikely to be financially viable for distributed generation applications. Active power control by varying the dc-link voltage of the back-to-back converter is presented to attenuate the flicker emission. However, a big dc-link capacitor is required, and the lifetime of the capacitor will be shortened to store of the fluctuation power in the dc link. An open-loop pitch control is used in and to investigate the flicker emission in high wind speeds, however, the pitch actuation system (PAS) is not taken into account. Because the pitch rate and the time delay of the PAS make great contributions to the results of the flicker emission of variable-speed wind turbines, it is necessary to take these factors into consideration. In recent years, IPC which is a promising way for loads reduction has been proposed, from which it is notable that the IPC for structural load reduction has little impact on the electrical power.

However in this paper, an IPC scheme is proposed for flicker mitigation of grid-connected wind turbines. The power oscillations are attenuated by individual pitch angle adjustment according to the generator active power feedback and the wind turbine azimuth angle in such a way that the voltage fluctuations are smoothed prominently, leading to the flicker mitigation. The influence of the flicker emission on the structural load is also investigated. The

FAST (Fatigue, Aerodynamics, Structures, and Turbulence) code which is capable of simulating three-bladed wind turbines is used in the simulation.

II. LITERATURE REVIEW

Various studies had been carried out by the researchers about the flicker emission of wind turbines during connected operation.[6] Authors have presented an analysis and the modelling of the flicker emission of wind turbines. Measurements compared with international standards were discussed. The paper concentrates on the theoretical aspects of the flicker algorithm, wind turbine characteristics and the generation of flicker during continuous operation of wind turbines.

Other researchers worked on the flicker study on variable speed wind turbines with doubly fed induction generators [5].Grid connected wind turbines may produce flicker during continuous operation. The paper presented a simulation model of a MW-level variable speed wind turbine with a doubly fed induction generator developed in the simulation tool of PSCAD/EMTDC. Flicker emission of variable speed wind turbines with doubly fed induction generators is investigated during continuous operation, and the dependence of flicker emission on mean wind speed, wind turbulence intensity, short circuit capacity of grid and grid impedance angle are analyzed. A comparison is done with the fixed speed wind turbine, which leads to a conclusion that the factors mentioned above have different influences on flicker emission compared with that in the case of the fixed speed wind turbine. Flicker mitigation is realized by output reactive power control of the variable speed wind turbine with doubly fed induction generator. Simulation results show the wind turbine output reactive power control provides an effective means for flicker mitigation regardless of mean wind speed, turbulence intensity and short circuit capacity ratio.

Mitigation of fatigue loads using individual pitch control of wind turbines based on FAST [2] is analysed in this paper, 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.

Researchers have worked for the comparison of various flicker mitigation techniques and proved the importance of Individual Pitch Control over other techniques. Flicker Mitigation by Individual Pitch Control of Variable speed wind turbines with DFIG [1].. This paper presents a simulation model for individual pitch control (IPC) of variable speed wind turbine with a doubly fed induction generator. This technique uses open source code FAST developed by National Renewable Energy Laboratory (NREI). The soul idea for this project is taken from this paper.

Flicker mitigation by active power control of variable speed wind turbines with full -scale back - to - back power converters [4] is presented using a simulation model of a megawatt-level variable speed wind turbine with a full-scale back-to-back power converter developed in the simulation tool of PSCAD/EMTDC. Flicker emission of this system is investigated. Reactive power compensation is mostly adopted for flicker mitigation. However, the flicker mitigation technique shows its limits, when the grid impedance angle is low in some distribution networks. A new method of flicker mitigation by controlling active power is proposed. It smoothes the active power oscillations from wind shear and tower shadow effects of the wind turbine by varying the dc-link voltage of the full-scale converter. Simulation results show that damping the active power oscillation by using the flicker mitigation controller is an effective means for flicker mitigation of variable-speed wind turbines with full-scale back-to-back power converters during continuous operation.\

III. WIND TURBINE CONFIGURATION

The overall scheme of a DFIG-based wind turbine system is shown in Fig.1, which consists of a wind turbine, gearbox, DFIG, a back-to-back converter which is composed of a rotor side converter (RSC) and GSC, and a dc-link capacitor as energy storage placed between the two converters. FAST is used to simulate the mechanical parts of wind turbine and the drive train. The pitch and converter controllers, DFIG, and power system are modeled by Simulink blocks.

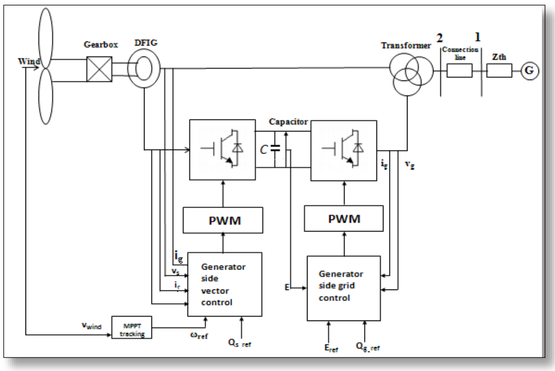

Fig.1 Overall scheme of the DFIG-based wind turbine system

A. (Fatigue, Aerodynamics, Structures, and Turbulence) FAST

The open source code FAST is developed at the National Renewable Energy Laboratory (NREL) and accessible and free to the public. FAST can be used to model both two and three bladed, horizontal axis wind turbines. It uses Blade Element Momentum 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 degree of freedoms (DOFs) 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 fast because of the use of the modal approach with fewer DOFs to describe the most important parts of turbine dynamics.

B. Mechanical drive-train

In order to take into account the effects of the generator and drive-train on the wind turbine, two mass model shown in Fig. 2. Which is suitable for transient stability analysis is used. The drive train modeling is implemented in FAST, and all values are referred to the wind turbine side.

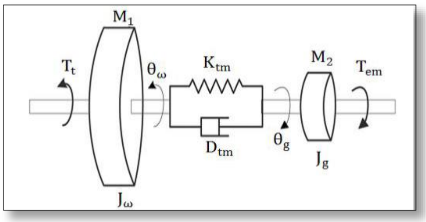

Fig 2 Two-mass model of the drive-train

The equations for modelling the drive-train are given by;

$$J_\omega \frac{d^2\theta_\omega}{dt^2} = T_t - D_{tm}\left(\frac{d\theta_\omega}{dt} - \frac{d\theta_\omega}{dt}\right) - K_{tm}(\theta_\omega - \theta_g)$$

$$J_g \frac{d^2\theta_\omega}{dt^2} = D_{tm}\left(\frac{d\theta_\omega}{dt} - \frac{d\theta_g}{dt}\right) + K_{tm}(\theta_\omega - \theta_g) - T_{em} \quad ;$$

Where *Jw* and *Jg* are the moment of inertia of wind turbine and generator, respectively, *Tt* , *Tem*, are the torque, respectively, *θw*, *θg* are the mechanical angle of wind turbine and generator, *Ktm* is the drive train torsional spring, *Dtm* is the drive train torsion damper.

C. Doubly Fed Induction Generation Model (DFIG)

The equivalent circuit of DFIG model shown in fig.3. All electrical variables are referred to the stator.

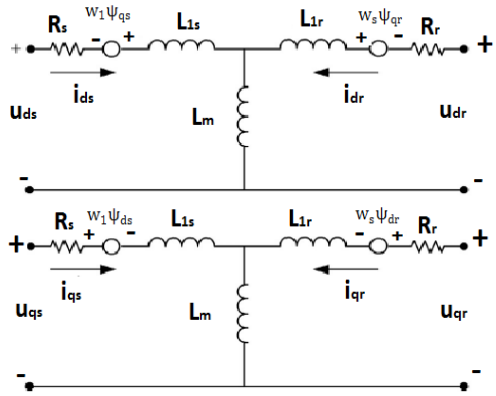

Fig. 3 d – q equivalent circuit of DFIG at synchronously rotating reference frame.

The DFIG control in this paper uses field oriented control which has been widely used in any 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. 4. 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.

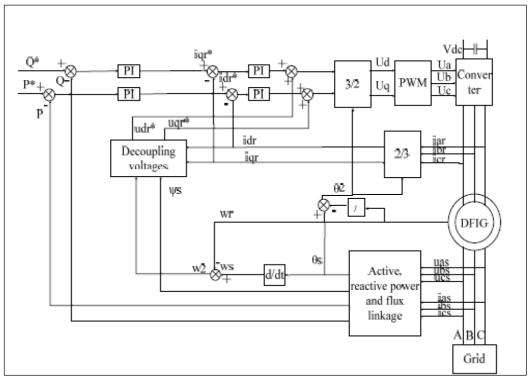

Fig. 4. Control scheme of DFIG based power system connected to the grid

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:

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

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.

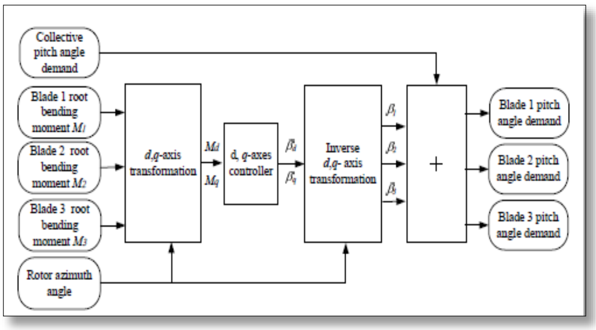

Fig. 5. Individual pitch control principle scheme

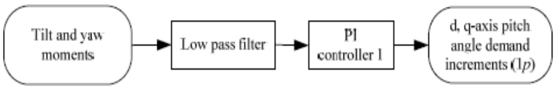

Fig. 6. The controller for d,q- axes

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:

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

where βd,q are the pitch angle demand increments for d,q-axes, and β1,2,3 are the three pitch angle demand increments for each blade respectively.

V. SIMULATION RESULTS

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.The flicker mitigation using IPC is tested in many wind speed conditions. The variable speed wind turbine with DFIG and back-to-back converter are simulated with the proposed IPC method.

TABLE I: PARAMETERS OF DFIG,WIND TURBINE AND PITCH CONTROLLER

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

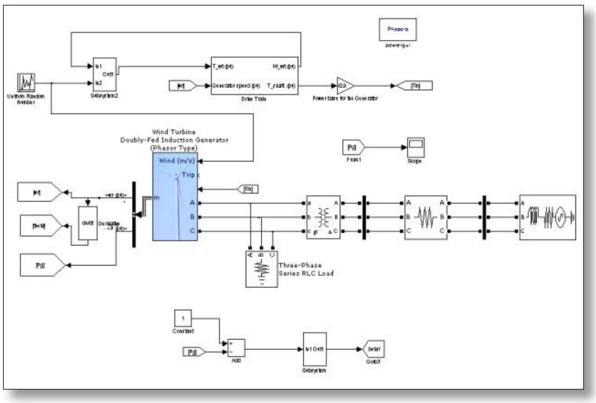

Fig.6. Simulink model for Proposed IPC method

Figs. 7 and 8 illustrate the short-term view and long-term view of the generator active power as well as the three pitch angles when the mean wind speed is above the rated wind speed. From these figures, it is shown that the generator active power to the grid is smoothed prominently.

It is noted that when a power wind speed variation, etc., one of the blades will accordingly reduce its pitch angle, thus the generator active power will not drop so dramatically, in such a way that the power oscillation is limited in a much smaller range, which is significant in flicker emission of variable speed wind turbines during continuous operation is damped evidently with IPC.

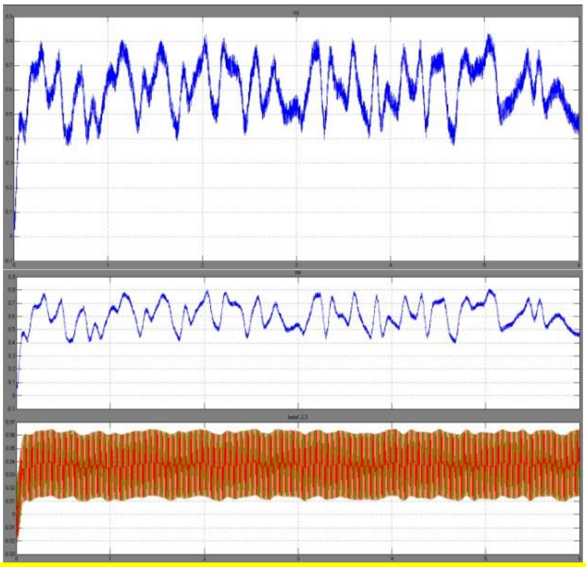

Fig.7 Short Term Profile of Generator active power without IPC and with IPC, w.r.t. pitch angle increments

As a consequence, the flicker level may be reduced by using IPC.

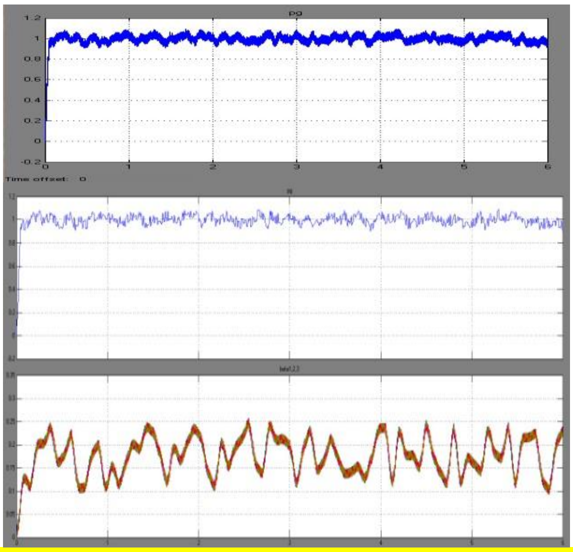

Fig.8 Long Term Profile of Generator active power without IPC and with IPC, w.r.t. pitch angle increments

The wind turbine system employing IPC is also carried out when the mean wind speed is below the rated wind speed. As a small pitch angle movement will contribute to high power variation, in this case, the minimum pitch angle βmin in the CPC loop is set to 2◦ (0.0349 rad), leaving a small amount of residual for IPC to mitigate the power oscillation.

The performance of the generator active power demonstrates that the IPC also works well in low wind speeds at the cost of some power loss due to the pitch movement.

Fig. 7 illustrates the variation of short-term flicker severity *P*st with different mean wind speed between the case without IPC and the case with IPC. It can be concluded that damping the active power oscillation by using IPC is an effective means for flicker mitigation of variable speed wind turbines during continuous operation at different wind speed.

Since many IPC algorithms can mitigate the wind turbine loads [9]–[11], the proposed new IPC which can mitigate the flicker emission might have some impact on the wind turbine
load. Due to the relationship between the rotor tilt and yaw moments and the blade root bending moments [9], it can also be inferred that the proposed IPC has little impact on the tilt and yaw loads.

There are also drawbacks of the proposed IPC method, such as loss of a small amount of wind energy in low wind speed and high demand of the PAS. There is an alternative flicker mitigation method, which is the turbine rotor speed control taking advantage of the large rotor inertia. In this way, the wind power fluctuations can be stored in the wind turbine rotor, leading to the flicker mitigation. However, this paper is focused on the IPC method. The IPC method for flicker mitigation proposed in this paper may be equally applicable to other types of variable speed wind turbines, such as a permanent magnet synchronous generator or a doubly salient permanent magnet generator, etc.

VI. CONCLUSION

This paper describes a method of flicker mitigation by IPC of variable-speed wind turbines with MW-level DFIG. The modelling of the wind turbine system is carried out using FAST and Simulink. On the basis of the presented model, flicker emission is analyzed and investigated in different mean wind speeds. To reduce the flicker emission, a novel control scheme by IPC is proposed.

The generator active power oscillation which leads to flicker emission is damped prominently by the IPC in both high and low wind speeds. It can be concluded from the simulation results that damping the generator active power oscillation by IPC is an effective means for flicker mitigation of variable speed wind turbines during continuous operation.

APPENDIX I

PARAMETERS OF THE WIND TURBINE WITH DFIG

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
Gearbox ratio	81
Drivetrain torsional spring (Nm/rad)	5.6e9
Drivetrain torsional damper (Nm/s)	1.0e7
Hub height(m)	82.39
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
Turbulence intensity	10%
Impedance magnitude of line 1-2 (Ω)	0.7642
Short circuit capacity ratio	10
Short circuit impedance	1.5125+j2.619
Grid impedance angle (degree)	60