Individual Pitch Control of Variable Speed Wind Turbines Using DFIG and Fuzzy Logic Controllers to Reduce Flicker

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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 paper 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. 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. The simulations are performed on the 1.5-MW upwind reference wind turbine model. Simulation results show that damping the generator active power by IPC with fuzzy logic controller is an effective means for flicker mitigation of variable speed wind turbines during continuous operation.
Keywords: Flicker, flicker mitigation, individual pitch control (IPC), variable speed wind turbine, fuzzy logic controller.

I. INTRODUCTION

Recently, the renewable energy, especially wind energy, has been paid much attention due to the energy shortage and environmental concern. As the penetration of the wind energy into the electrical power grid is extensively increased, the influence of the wind turbine systems on the frequency and voltage stability becomes more and more significant [1]–[4]. Consequently, the power control technique of the wind turbines is also getting more important in the view point of grid integration. The variable-speed, variable-pitch wind turbine systems typically have two operating regions according to the wind speed. In the partial-load region where the wind speed is lower than the rated-wind speed, the turbine speed is controlled at the optimal value so that the maximum energy is extracted from the wind turbine [5], [6]. In the full-load region where the wind speed exceeds its rated value, the generator output power is limited at the rated value by controlling the pitch angle since the capacity of the generator and converter are limited [7]–[9]. On the contrary, the pitch regulation can be used for output power smoothening at the partial-load region [10], [11]. For limiting the aerodynamic power captured by the wind turbine at the high-wind speed regions, several pitch angle control methods have been suggested. The proportional–integral (PI) or proportional––integral–derivative (PID) based-pitch angle controllers have been often used for the power regulation [12]. The disadvantage of this method is that the control performance is deteriorated when the operating points are changed since the controller design is based on the turbine model which is linearized at the operating points by a small signal analysis.

Another scheme using the H_∞ controller with a linear matrix inequality approach was proposed [13], which gives a good performance of the turbine output power as well as the robustness to the variations of the wind speed and the turbine parameters. However, it is rather complex since the parameters of the model and the controller need to be redesigned due to the changes of the weighting functions by the constraints. 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 [14].

Because the pitch rate and the time delay of the pitch actuation system (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, Individual pitch control (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.

II. WIND TURBINE CONFIGURATION

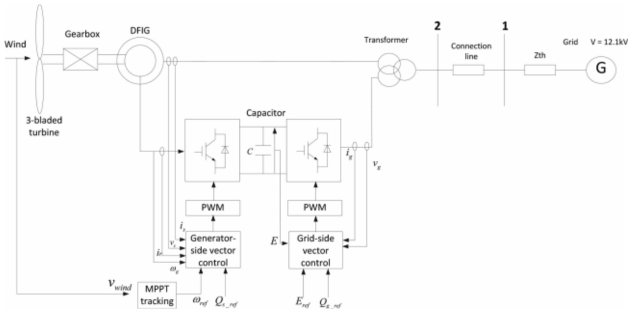

Fig. 1. Block diagram of DFIG based wind turbine system

The overall scheme of a doubly fed induction generator (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 grid side converter (GSC), and a dc-
link capacitor as energy storage placed between the two converters. The pitch and converter controllers, DFIG, and power system are modeled by Simulink blocks.

A. Mechanical Drivetrain

In order to take into account the effects of the generator and drivetrain on the wind turbine, two-mass model shown in Fig. 2

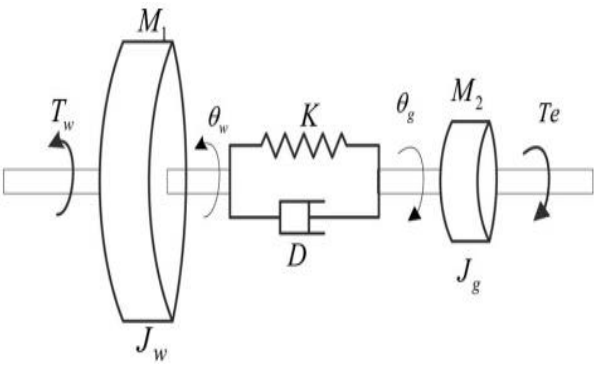

Fig. 2. Two-mass model of the drivetrain.

Which is suitable for transient stability analysis is used [13]. The equations for modeling the drivetrain are given by

$$J_w \frac{d^2\theta_w}{dt^2} = T_w - D\left(\frac{d\theta_w}{dt} - \frac{d\theta_g}{dt}\right) - K(\theta_w - \theta_g) \quad (1)$$

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

where J_w and J_g are the moment of inertia of wind turbine and generator, respectively, T_w,T_e are the wind turbine torque and generator electromagnetic torque, respectively, θ_w , θ_g are the mechanical angle of wind turbine and generator, K is the drivetrain torsional spring, D is the drivetrain torsional damper.

B. DFIG Model

The model of the DFIG is based on dq equivalent model shown in Fig. 3. All electrical variables are referred to the stator. u_{ds}, u_{qs}, u_{dr}, u_{qr} , i_{ds}, i_{qs}, i_{dr}, i_{qr} and ψ_{ds}, ψ_{qs}, ψ_{dr}, ψ_{qr} are the voltages, currents, and flux linkages of the stator and rotor in d- and q-axes, r_s and r_r are the resistances of the stator and rotor windings, L_s,L_r,L_m are the stator, rotor, and mutual inductances, L_{1s},L_{1r} are the stator and rotor leakage inductances, ω_1 is the speed of the reference frame, ω_s is the slip angular electrical speed. The RSC of DFIG is controlled in a synchronously rotating d-q reference frame with the d-axis aligned along the stator flux position. The electrical torque T_e, active power P_s, and reactive power Q_s of DFIG can be expressed by [1]

$$T_e = \frac{3}{2} p \frac{L_m}{L_s} \psi_s i_{qr}$$
(3)

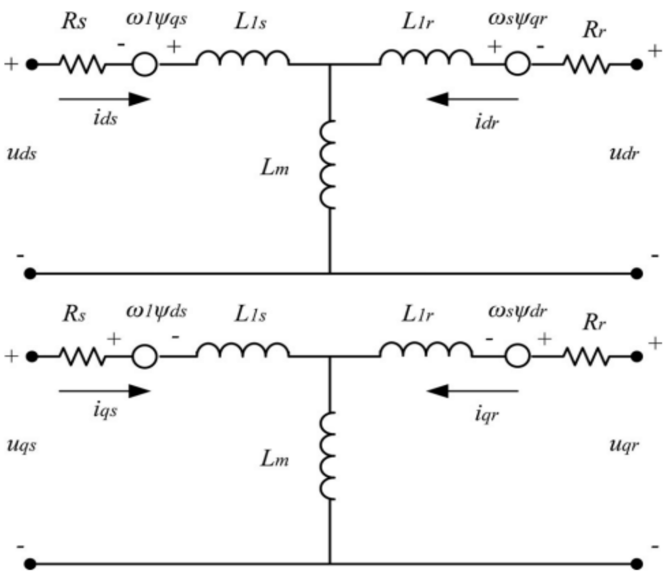

Fig. 3. D − q equivalent circuit of DFIG at synchronously rotating reference frame.

$$P_s = -\frac{3}{2} u_s \frac{L_m}{L_s} i_{qr}$$
(4)

$$Q_s = \frac{3}{2} \frac{\psi_s}{L_s} u_s - \frac{3}{2} u_s \frac{L_m}{L_s} i_{dr}$$
(5)

Where p is the number of pole pairs, ψ_s is the stator flux, us is the magnitude of the stator phase voltage. From (4) and (5), due to the constant stator voltage, the active power and reactive power can be controlled via i_{qr} and i_{dr} .

III. WIND TURBINE CONTROL AND FLICKER EMISSION ANALYSIS

For a DFIG-based variable speed wind turbine, the control objective is different according to different wind speed. In low wind speed, the control goal is to keep the tip speed ratio optimum, so that the maximum power can be captured from the wind. In high wind speed, since the available power is beyond the wind turbine capacity, which could overload the system, the control objective is to keep the extracted power constant at its rated value.

A. Control of Back-to-Back Converter

Vector control techniques are the most commonly used methods for a back-to-back converter in a wind turbine system. Two vector control schemes are illustrated, respectively, for the RSC and GSC, as shown in Fig. 1, where v_s, and is are the stator voltage and current, i_r is the rotor current, v_g is the grid voltage, i_g is the GSC currents, ω_g is the generator speed, E is the dc-link voltage, P_{s_ref} , and Q_{s_ref} are the reference values of the stator active and reactive power, Q_{r_ref} is the reference value of the reactive power flow between the grid and the

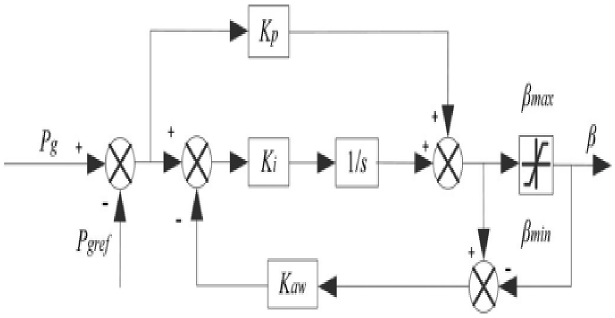

Fig. 4. PI controller with anti-wind up.

GSC, E_{ref} is the reference value of the dc-link voltage, C is the dc-link capacitor. The vector control objective for RSC is to implement maximum power tracking from the wind by controlling the electrical torque of DFIG. The reference value of the generator speed ω_{ref} is obtained via a lookup table to enable the optimal tip speed ratio. The objective of GSC is to keep the dc-link voltage constant, while keeping sinusoidal grid currents. It may also be responsible for controlling the reactive power flow between the grid and the grid-side converter by adjusting Q_{g_ref} . 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 [1].

B. Pitch Control

Normally, pitch control is used to limit the aerodynamic power captured from the wind. In low wind speeds, the wind turbine should simply try to produce as much power as possible, so there is no need to pitch the blades. For wind speeds above the rated value, the pitch control scheme is responsible for limiting the output power.

The PI controller used for adjusting the pitch angles works well in normal operation, however, the performance of the pitch control system will degrade when a rapid change in wind speed from low to high wind speed is applied to the turbine rotor. It takes a long time for a positive power error contribution to cancel the effects of the negative pitch angle contribution that has been built up from integration of these negative power errors.

The integrator anti-windup scheme is implemented as shown in Fig. 4, in which the ant windup term with gain Kaw is fed back to the integrator only. This prevents the integrated power error from accumulating when the rotor is operating in low wind speeds. The value for Kaw may be turbine dependent. When the pitch angle is not saturated, this ant windup feedback term is zero [14].

C. Flicker Emission in Normal Operation

As discussed in Section I, flicker emission of a grid-connected wind turbine system is induced by voltage fluctuations which are caused by load flow changes in the network, so it is necessary to analyze the electrical power to the grid. Therefore, a simulation is conducted when the mean wind speed is 13 m/s based on the model as shown in Fig. 1. It is clearly seen that in addition to the 3p frequency, 6p, 9p, and higher frequencies are also included in the generator output power. These components will induce voltage fluctuations and flicker emission in the power grid. Further, the flicker emission of a variable-speed wind turbine with DFIG is studied. The level of flicker is quantified by the short-term flicker severity P_{st}, which is normally measured over a 10-min period [6].

IV. INDIVIDUAL PITCH CONTROL FOR FLICKER MITIGATION

This section concentrates on flicker mitigation of variablespeed wind turbines with DFIG during continuous operation using IPC.

When the wind speed is above the rated wind speed, the pitch angle should be tuned by a 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 consideration. For attenuating the generator power oscillation caused by the 3p effect, each of the three pitch angles can be added by a small pitch angle increment, which is dependent on the generator active power and wind turbine azimuth angle.

When the wind speed is below the rated wind speed, usually the control objective of the 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 output of the CPC should leave a small amount of residual for pitch movement. This means a small part of wind energy will be lost. Based on this concept, a novel IPC strategy is proposed. The control scheme is shown in Fig. 5. The control scheme consists of two control loops: CPC loop and IPC loop.

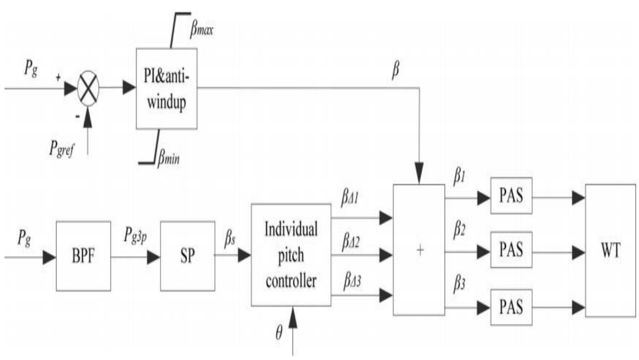

Fig. 5. Proposed individual pitch control scheme.

The CPC loop is responsible for limiting the output power. In this loop, P_{g_ref} is the reference generator power which can be calculated according to different wind speed, P_g is the generator active power, β is the collective pitch angle, of which the minimum value β_{min} can be obtained by simulations under different wind speed such that the mitigation of generator power fluctuation should compromise the wind power loss. In the individual pitch control loop, the band pass filter (BPF) is to let the frequency of 3p generator active power P_{g3p} through and block all other frequencies. P_{g3p} is fed to the signal processing (SP) block, since the power signal has to be transferred to the pitch signal β_s which subsequently is passed to the individual pitch controller to output a pitch increment for a specific blade. The three pitch angles $\beta_{1,2,3}$ which are, respectively, the sum of collective pitch angles, and three pitch angle increments are sent to the PAS to adjust the three pitch angles to implement the mitigation of the generator active power oscillation.

A. Design of BPF

The transfer function of the BPF can be expressed as follows:

$$F(s) = \frac{Ks}{s^2 + (\omega_c/Q)s + \omega_c^2} \tag{6}$$

Where ω_c is the center frequency, K is the gain, and Q is the quality factor. ω_c which corresponds to the 3p frequency can be calculated by the measurement of the generator speed ω_g. $\omega_c = 3\omega_g /N$, where N is the gear ratio. The gain of the BPF at the center frequency is designed as 1 in order to let all the 3p frequencies pass the filter ($F(s) = KQ/\omega_c = 1$). Q which is responsible for the bandwidth of the BPF should be adjusted to let only the 3p component pass. In this case, Q is designed as $Q = \omega_c$.

B. Signal Processing

The SP block has to produce a pitch signal to offset the power oscillation, in such a way that the generator power will oscillate in a much smaller range.

Due to the time delay caused by the PAS and the powertransfer from wind turbine rotor to the power grid, etc., the phase of the generator active power lags the phase of the pitch signal. In order to produce the correct phase angle shift of the SP block, it is very important to get the phase deviation of the component with 3p frequency of β and $Pg3p$. For this reason, the system is operated in high wind speed without the IPC loop. In this case, the collective pitch angle β contains the component with 3p frequency. The phase angle shift can be obtained by the component of β with 3p frequency and P_{g3p}.The SP block can be implemented with a first-order lag element, which delays the phase angle at 3p frequency. The SP block can be represented as follows:

$$F_{\mathrm{sp}}(s) = \frac{K_{\mathrm{sp}}}{T_{\mathrm{sp}}s + 1} \tag{7}$$

The angular contribution of (7) is

$$\delta(\omega) = -\arctan(\omega T_{\mathrm{sp}}) \tag{8}$$

Hence, the time constant T_{sp} can be calculated with the required angular contribution δ at ω_{3p}, shown as follows:

$$T_{\mathrm{sp}} = -\frac{\tan\delta}{\omega_{3p}}$$

Where ω_{3p} is the center frequency of the BPF. The gain K_{sp} can be tuned by testing, as it has no contribution to the phase shift of the SP block. Increasing K_{sp} can accelerate the flicker mitigation; however, a big value of K_{sp} might increase the flicker emission of the wind turbine.

C. Individual Pitch Controller Design

The individual pitch controller will output the three pitch angle increments $\beta_{\Delta1,\Delta2,\Delta3}$ for each blade based on the pitch signal βs 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 I. For example, if the azimuth angle belongs to the area of $(0, 2\pi/3)$, then $\beta_{\Delta2}$ equals β_s, and both $\beta_{\Delta1}$ and $\beta_{\Delta3}$ equal 0. The three pitch increments will be, respectively, added with the collective pitch angle to give three total pitch angle demands. The three pitch angle signals will be sent to the PAS. The PAS can be represented using a first-order transfer function:

TABLE I
Control Principle of Individual Pitch Controller

azimuth angle θ	β_s
$0< \theta <2\pi/3$	β_{A2}
$4\pi/3> \theta >2\pi/3$	β_{A1}
$2\pi> \theta >4\pi/3$	β_{A3}

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

Where T_{pas} which is a turbine dependent time constant of the PAS. In this case T_{pas} = 0.1. The control scheme shown in Fig. 7 is used for mitigation of the 3p component of the generator active power, leading to the reduction of the flicker emission which is caused by the 3p effect. Similar method can also be used to reduce the 6p component of the generator active power. However, this 6p component mitigation needs a much faster pitch actuation rate, which is not taken into account in this paper.

V. FUZZY LOGIC CONTROL

L. A. Zadeh presented the first paper on fuzzy set theory in 1965. Since then, a new language was developed to describe the fuzzy properties of reality, which are very difficult and sometime even impossible to be described using conventional methods. Fuzzy set theory has been widely used in the control area with some application to power system [5]. A simple fuzzy logic control is built up by a group of rules based on the human knowledge of system behavior. Matlab/Simulink simulation model is built to study the dynamic behavior of converter. Furthermore, design of fuzzy logic controller can provide desirable both small signal and large signal dynamic performance at same time, which is not possible with linear control technique. Thus, fuzzy logic controller has been potential ability to improve the robustness of converters. The basic scheme of a fuzzy logic controller is shown in Fig 6 and consists of four principal components such as: a fuzzy fication interface, which converts input data into suitable linguistic values; a knowledge base, which consists of a data base with the necessary linguistic definitions and the control rule set; a decision-making logic which, simulating a human decision process, infer the fuzzy control action from the knowledge of the control rules and linguistic variable definitions; a de-fuzzification interface which yields non fuzzy control action from an inferred fuzzy control action [10].

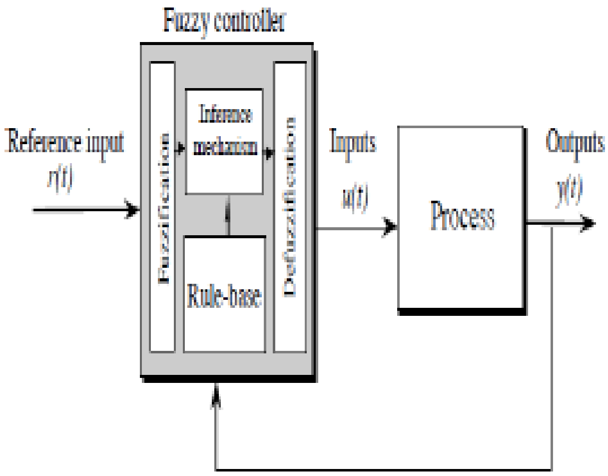

Fig.6. General Structure of the fuzzy logic controller.

The fuzzy control systems are based on expert knowledge that converts the human linguistic concepts into an automatic control strategy without any complicated mathematical model [10].

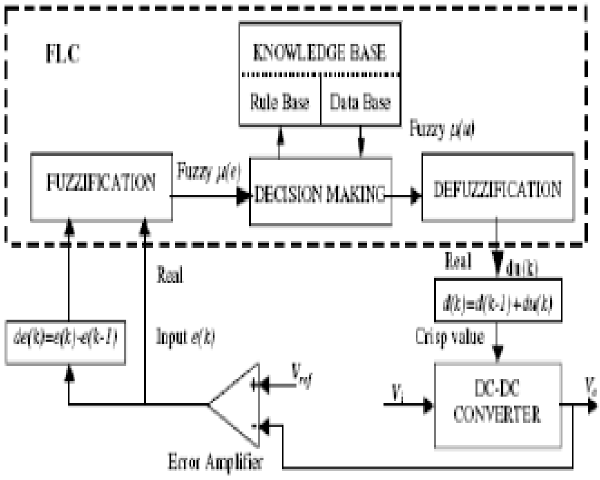

Fig.7. Block diagram of the Fuzzy Logic Controller (FLC)for proposed converter.

VI.MATLAB/SIMULATION RESULTS

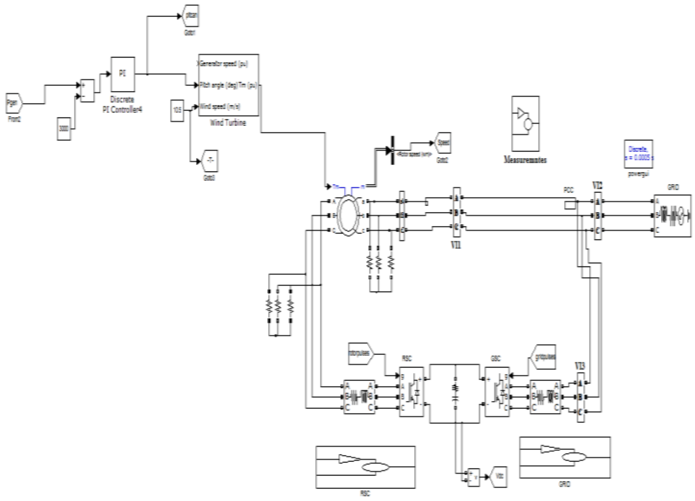

Fig.8.Matlab/Simulation model of high wind without IPC.

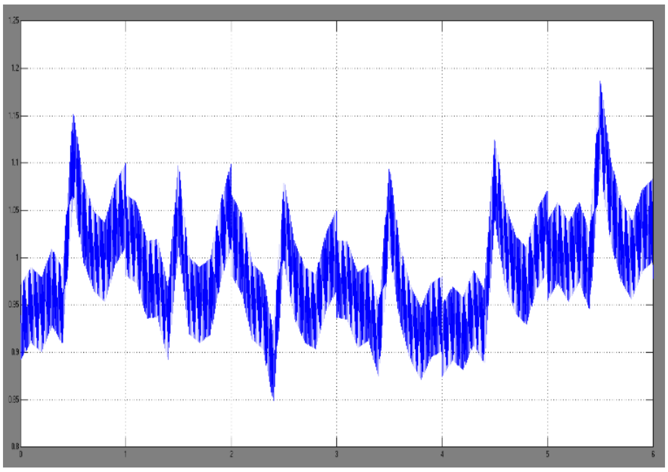

Fig. 9. Short-term view of the generator active power without IPC.

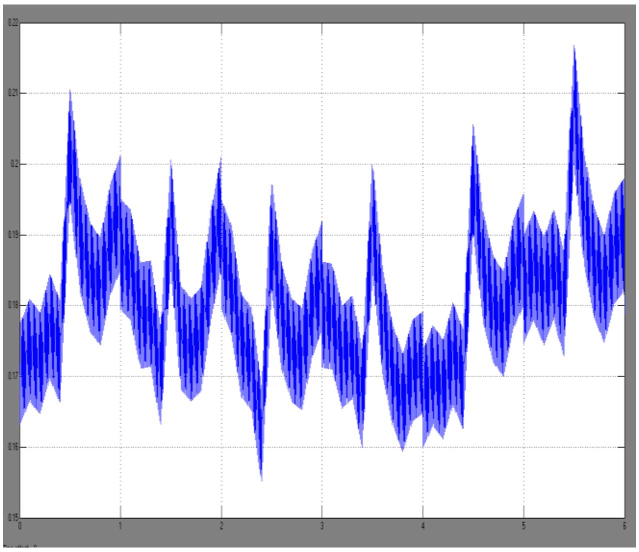

Fig. 10. Short-term view of the without IPC of individual pitch angles (high wind speed).

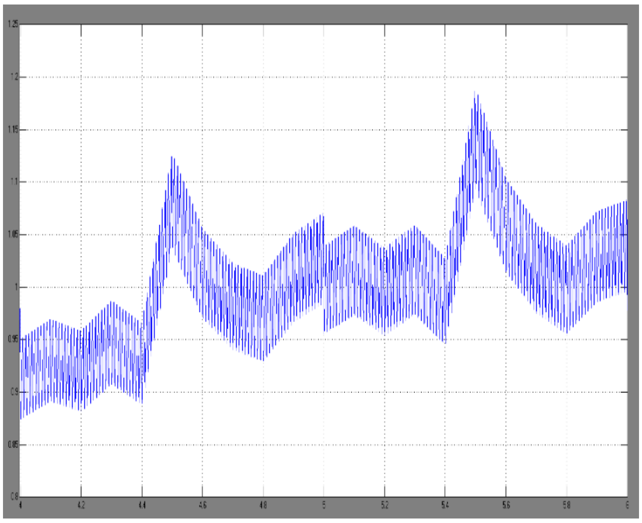

Fig. 11. Short-term view of the generator active power with IPC.

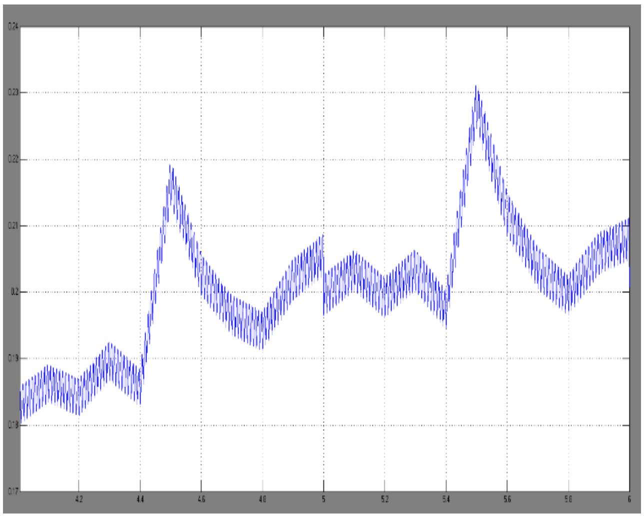

Fig. 12. Short-term view of the with IPC of individual pitch angles (high wind speed).

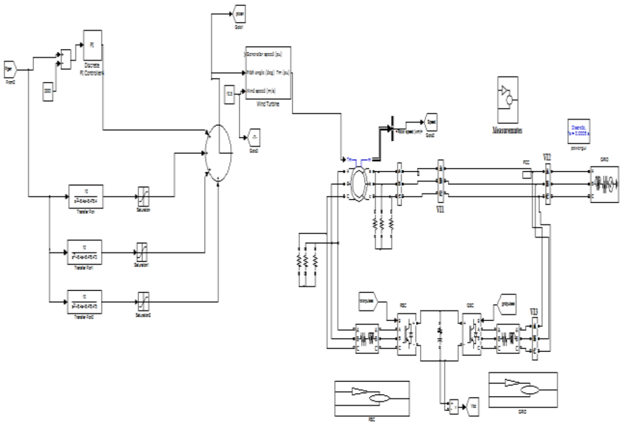

Fig.13.Matlab/Simulation model of high wind with IPC.

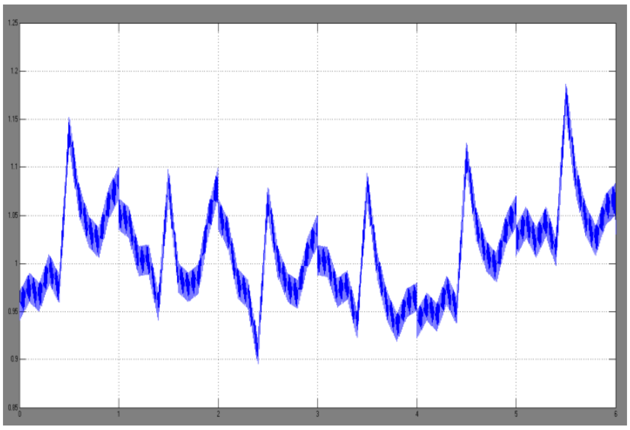

Fig. 14. Long-term view of the generator active power without IPC.

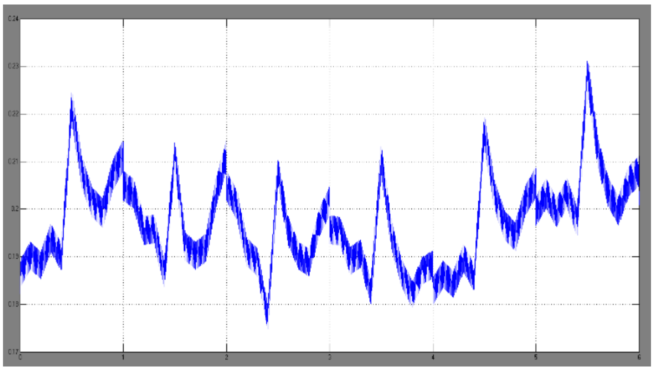

Fig. 15. Long-term view of the without IPC and pitch angle (high wind speed).

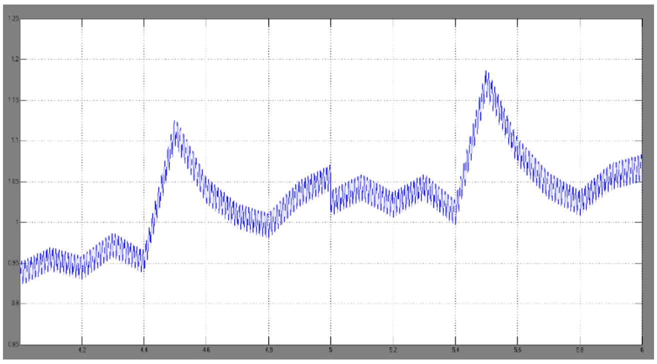

Fig. 16. Long-term view of the generator active power with IPC.

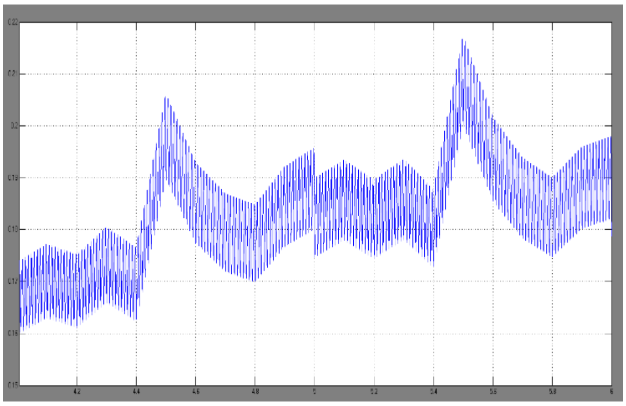

Fig. 17. Long-term view of the generator with IPC and pitch angle (high wind speed).

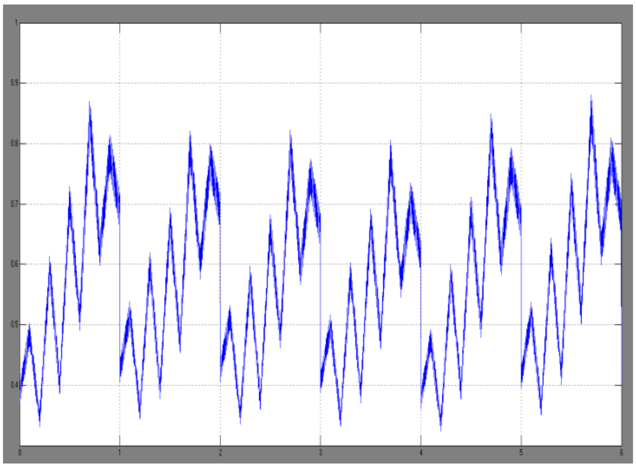

Fig. 18. Long-term view of the generator active power without IPC.

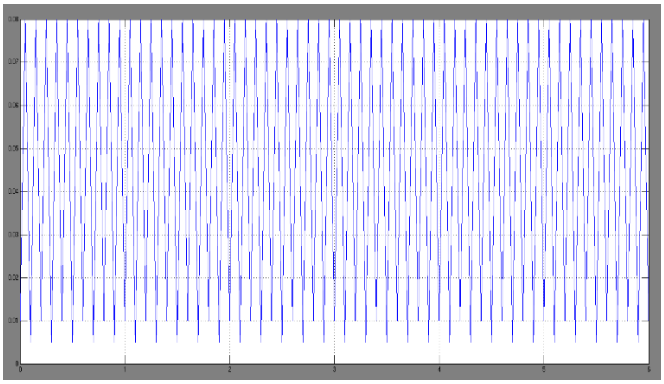

Fig. 19. Long-term view of the generator without IPC and pitch angle.

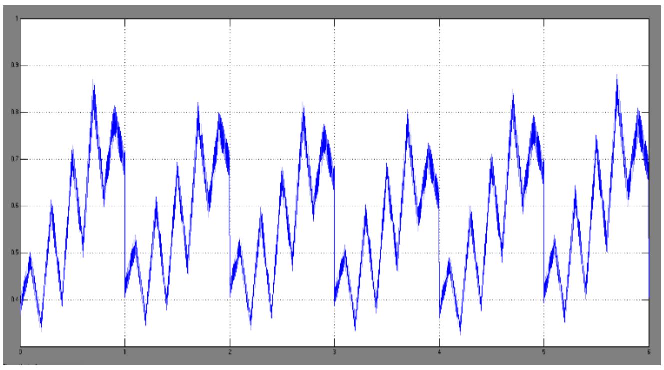

Fig. 20. Long-term view of the generator active power with IPC.

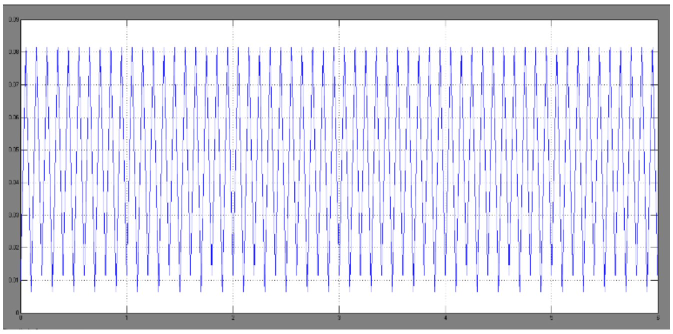

Fig. 21. Long-term view of the generator active power and with IPC.

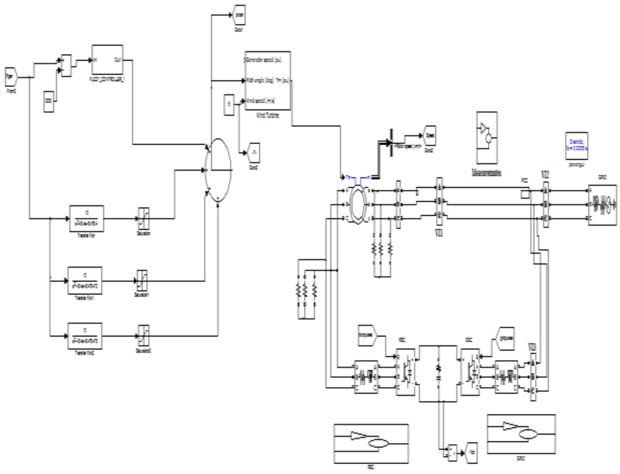

Fig.22.Matlab/Simulation model of high wind without IPC and fuzzy logic controller.

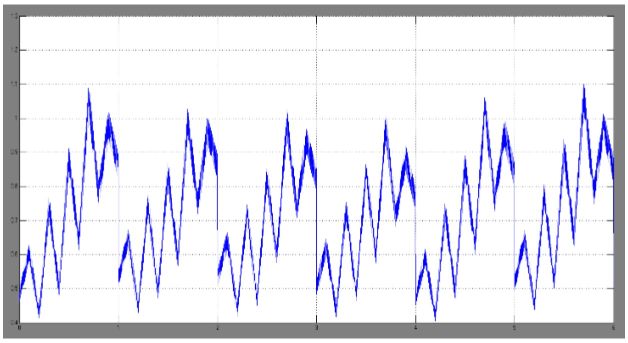

Fig. 23. Long-term view of the generator active power with IPC and fuzzy logic controller.

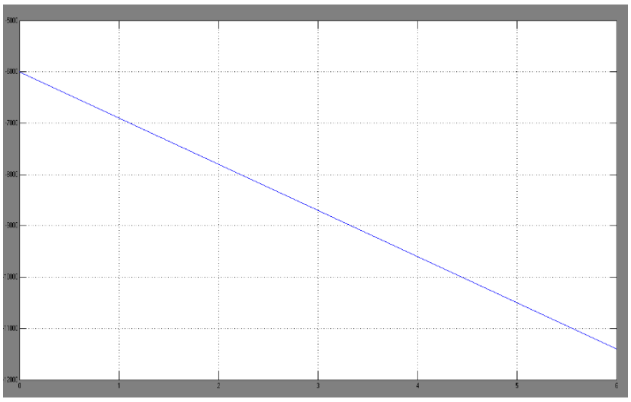

Fig.24. Long-term view of the generator active power and with IPC and fuzzy logic controller.

VII. CONCLUSION

In this paper a comparison between two different pitch control techniques has been done. The conventional individual pitch control has been replaced by fuzzy logic controller based pitch control technique. To reduce the

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flicker emission, a control scheme by IPC is there previously. This paper proposes implementation of Fuzzy logic control in pitch angle control for DFIG based wind energy conversion. Fuzzy logic control is design with mamdani 49 rules, it effectively controls the pitch angle to get better response in power generation and voltage generation maintained constant value. The Simulation and modeling proposed model is designed in Matlab/Simulink software. The simulation results show that fuzzy controller effectively regulates pitch angle of wind turbine. And it is also been observed that the proposed fuzzy controller is more effective than the conventional IPC scheme.

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