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An Enhanced Pitch Control Using Fuzzy Logic for Stability Improvement in DFIG based Wind Energy Systems

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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. To mitigate the flickers we were using an individual pitch control technique in the earlier days. In this paper, an advanced pitch angle control strategy based on the fuzzy logic is proposed for the variable-speed wind turbine systems, in which the generator speed error and change speed error are used as control input variables for the fuzzy logic controller (FLC). The pitch angle reference is produced by the FLC, which can compensate for the nonlinear characteristic of the pitch angle to the wind speed. This paper presents principal conversion of wind energy, wind turbine linearization and dynamic modeling are derived. The fuzzy logic controller is employed for change blade angle of wind turbine and constant power can be achieve. The block diagram of proposed pitch control which consists of pitch controller, actuator model and turbine linearized modeled by using Matlab/Simulink software.**

***Index Terms*—Flicker, flicker mitigation, individual pitch control (IPC), variable speed wind turbine.**

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 V_{rated}, 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 [1], [12]–[15]. 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 $H\infty$ controller with a linear matrix inequality approach was proposed [16], 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 [3]. 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 [4], [5]. 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.

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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 [6]. However, the flicker mitigation technique shows its limits in some distribution networks where the grid impedance angle is low [7]. 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 [8]. It is difficult for a grid-side converter (GSC) to generate this amount of reactive power, es-pecially 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 con-trol by varying the dc-link voltage of the back-to-back converter is presented to attenuate the flicker emission [8]. 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 [6] and [8] 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 [9]–[11], 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 volt-age 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 [12] which is capable of simulating three-bladed wind turbines is used in the simulation. In this paper we are enhancing the control technique for converters in the DFIG based wind energy system so that the need of IPC can be eliminated. So we can avoid the cost for the equipment that is used for IPC technique. 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. In this paper, 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.

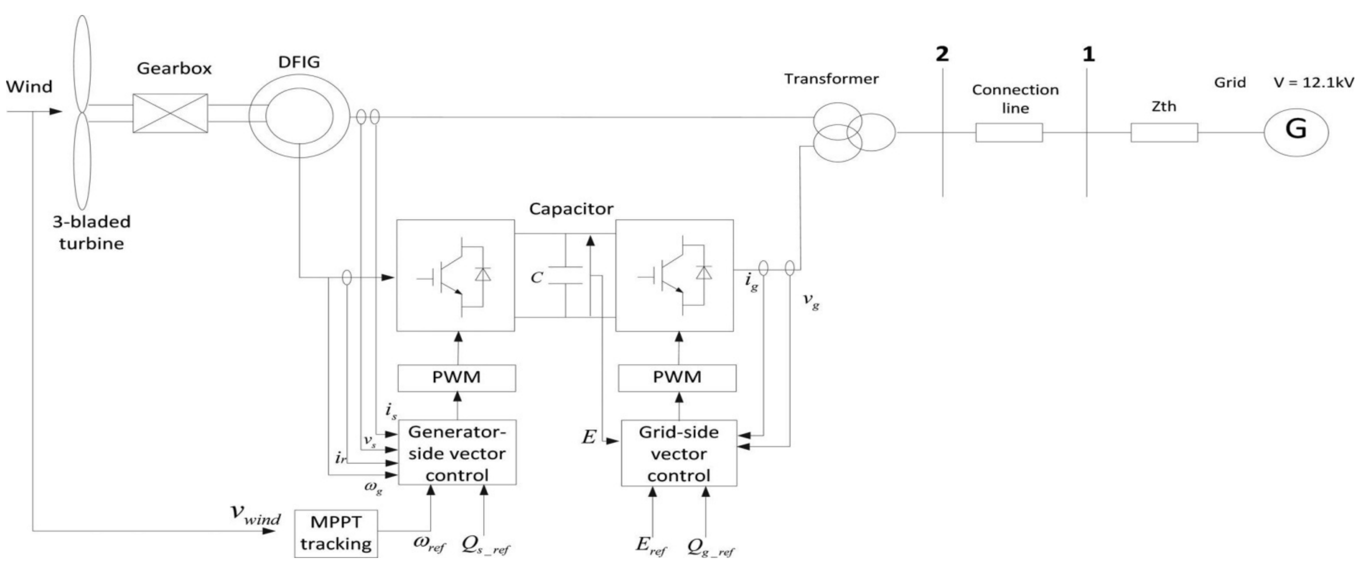

Fig. 1 Overall scheme of the DFIG-based wind turbine system.

II. WIND TURBINE MODELING

Wind turbines convert the kinetic energy present in the wind into mechanical energy by means of producing torque. Since the energy contained by the wind is in the form of kinetic energy, its magnitude depends on the air density and the wind velocity. The wind power developed by the turbine is given by the equation (1) [1-10]:

$$Pm = \frac{1}{2} * Cp(\lambda, \beta)\rho A v^3 \quad (1)$$

Where is the Power Co-efficient, is the air density in kg/m3, *A* is the area of the turbine blades in m2 and *V* is the wind velocity in m/sec. The power coefficient is defined as the power output of the wind turbine to the available power

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in the wind regime. This coefficient determines the "maximum power" the wind turbine can absorb from the available wind power at a given wind speed. It is a function of the tip-speed ratio ( ) and the blade pitch angle (The blade pitch angle can be controlled by using a "pitch-controller" and the tip-speed ratio (TSR) is given as

$$\lambda = \frac{wR}{v} \qquad (2)$$

Where λ is the rotational speed of the generator and R is radius of the rotor blades.

Hence, the TSR can be controlled by controlling the rotational speed of the generator. For a given wind speed, there is only one rotational speed of the generator which gives a maximum value of , at a given β. This is the major principle behind "maximum-power point tracking" (MPPT) and a wind turbine needs to be designed keeping this strategy in mind.

The turbine in DFIG system is the combination of blades and hub. Its function is to convert the kinetic energy of the wind into the mechanical energy, which is available for the generator. In general the detailed models of the turbine are used for the purpose of design and mechanical testing only. The stability studies done in this paper do not require detailed modeling of the wind turbine blades and hence it is neglected in this paper. Inputs to the wind turbine are the wind speed, pitch angle and the rotor speed and the output from the wind turbine is the mechanical torque.

A. Doubly Fed Induction Generator

The topology of a DFIG is shown in Fig. 1. The stator of a DFIG is connected to the power grid directly, while the rotor is connected to the grid through two back-to-back pulse width modulation (PWM) converters, i.e. rotor-side converter and grid-side converter. The grid-side converter usually works at the unity power factor of 1 and is in charge of maintaining a constant DC-link voltage for the rotor-side converter. The decoupling control of active and reactive power of the DFIG is achieved by adjusting the rotor's current and voltage through the rotor-side converter.

B. Operating Principle of the Wind Turbine Doubly-Fed Induction Generator

The power flow, illustrated in the fig.2 called the Power Flow, is used to describe the operating principle. In this figure the followings parameters are used:

Pm - Mechanical power captured by the wind turbine and transmitted to the rotor
P_s - Stator electrical power output
P_r - Rotor electrical power output
P_{gc} - C_{grid} electrical power output
Q_s - Stator reactive power output
Q_r - Rotor reactive power output
Q_{gc} - C_{grid} reactive power output
T_m - Mechanical torque applied to rotor
T_{em} - Electromagnetic torque applied to the rotor by the generator
W_r - Rotational speed of rotor
W_s - Rotational speed of the magnetic flux in the air-gap of the generator, this speed is named synchronous speed. It is proportional to the frequency of the grid voltage and to the number of generator poles.
J - Combined rotor and wind turbine inertia coefficient.

The mechanical power and the stator electric power output are computed as follows:

$$Pm = Tm * Wr \qquad (3)$$

$$Ps = Tem * Ws \qquad (4)$$

For a loss less generator the mechanical equation is

$$J * \frac{dWr}{dt} = Tm - Tem \qquad (5)$$

In steady-state at fixed speed for a loss less generator

$$Tm = Tem \;\&\; Pm = Ps + Pr \qquad (6)$$

It follows that:

$$Pr = Pm - Ps = TmWr - TemWs = Tm * \frac{Ws - Wr}{Ws} \quad (7)$$

$$S = \frac{Ws - Wr}{Ws} \qquad (8)$$

where s is defined as the slip of the generator:

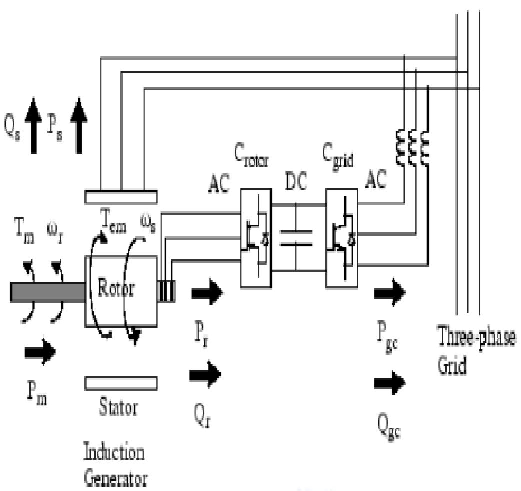

Fig. 2 The Power Flow

Generally the absolute value of slip is much lower than 1 and, consequently, Pr is only a fraction of Ps. Since Tm is positive for power generation and since is positive and constant for a constant frequency grid voltage, the sign of Pr is a function of the slip sign. Pr is positive for negative slip (speed greater than synchronous speed) and it is negative for positive slip (speed lower than synchronous speed). For super-synchronous speed operation, Pr is transmitted to DC bus capacitor and tends to rise the DC voltage. For sub-synchronous speed operation, Pr is taken out of DC bus capacitor and tends to decrease the DC voltage. Cgrid is used to generate or absorb the power Pgc in order to keep the DC voltage constant. In steady-state for a loss less AC/DC/AC converter Pgc is equal to Pr and the speed of the wind turbine is determined by the power Pr absorbed or generated by Crotor. The power control will be explained below.

The phase-sequence of the AC voltage generated by Crotor is positive for sub-synchronous speed and negative for super-synchronous speed. The frequency of this voltage is equal to the product of the grid frequency and the absolute value of the slip.

Crotor and Cgrid have the capability of generating or absorbing reactive power and could be used to control the reactive power or the voltage at the grid terminals.

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 *vs* , and *is* are the stator voltage and current, *ir* is the rotor current, *vg* is the grid voltage, *ig* is the GSC currents, *wg* is the generator speed, *E* is the dc-link voltage, *Ps* ref , and *Qs* ref are the reference values of the stator active and reactive power, *Qr* ref is the reference value of the reactive power flow between the grid and the 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 *Qg* 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 antiwindup scheme is implemented as shown in Fig. 4, in which the antiwindup term with gain *K*aw 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 *K*aw may be turbine dependent. When the pitch angle is not saturated, this antiwindup 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 high wind speeds, where the wind turbine reaches rated power, the flicker level decreases due to the introduction of PI blade pitch control which could reduce the power oscillation in low frequency prominently, but it cannot effectively mitigate the power oscillations with 3p, 6p, 9p, and higher frequencies. As the power oscillation is bigger for higher wind speeds when the wind speed is above the rated wind speed, the flicker level continues to rise with the increase of mean wind speed.

IV. INDIVIDUAL PITCH CONTROL FOR FLICKER MITIGATION

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

The flicker emission produced by grid connected wind turbines during continuous operation is mainly caused by fluctuations in the generator active power. As illustrated in

Fig. 3, the flicker emission will be mitigated effectively if the 3p and higher harmonics of the generator power can be reduced.

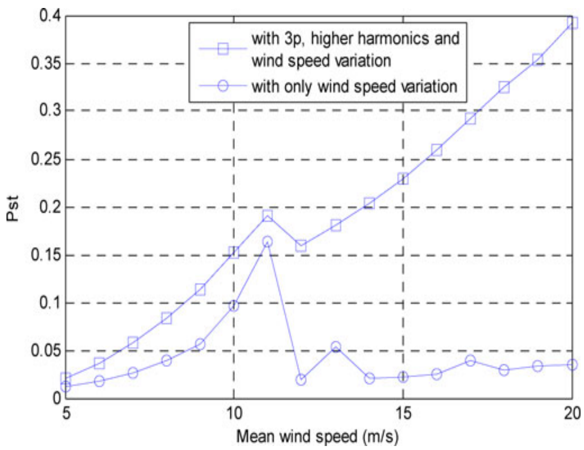

Fig. 3 Flicker severity *P*st between the cases with 3p, higher harmonics and wind speed variation (square), and the case with only wind speed variation (circle).

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. 4. The control scheme consists of two control loops: CPC loop and IPC loop.

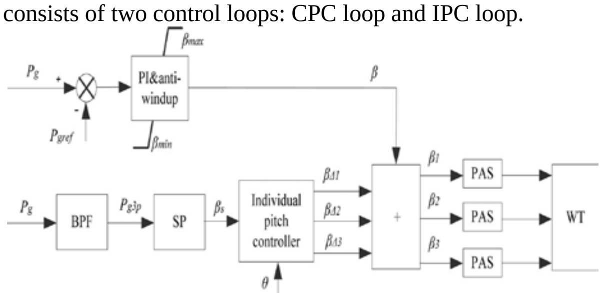

Fig. 4 Existed individual pitch control scheme.

The CPC loop is responsible for limiting the output power. In this loop, *Pg* ref is the reference generator power which can be calculated according to different wind speed, *Pg* is the generator active power, β is the collective pitch angle, of which the minimum value βmin 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 *Pg*3*p* through and block all other frequencies. *Pg*3*p* is fed to the signal processing (SP) block, since the power signal has to be transferred to the pitch signal βs which subsequently is passed to the individual pitch controller to output a pitch increment for a specific blade. The three pitch angles β1,2,3 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.

The individual pitch controller will output the three pitch angle increments $\beta\Delta 1, \Delta 2, \Delta 3$ 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, 2π/3), then $\beta\Delta 2$ equals βs , and both $\beta\Delta 1$ and $\beta\Delta 3$ 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:

$$F(s) = \frac{1}{TpasS+1} \qquad (9)$$

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. PITCH ANGLE CONTROL USING FUZZY LOGIC CONTROLLER

Wind turbine consists of generally three or two blades, a controller, a servo motor, a rotor rotation sensor, a generator and other mechanical components. The pitch angle of the blade is control by servomotors. To measure

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speed of wind turbine rotor rotary encoder is used. Fig. 5 shows a block diagram of wind turbine pitch angle control using Fuzzy Logic controller (FLC) for less rated wind speed. By controls the blade pitch angle to wind turbine speed is maximizes. From Fig. 6 rotor speed in rpm from encoder is compared with reference speed of rotor. The Fuzzy logic controller considers rotor speed error and change in error as inputs.

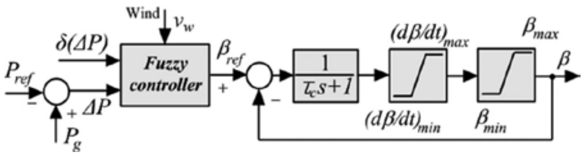

Fig. 5 Block diagram of pitch controller using fuzzy logic

Fig 6 shows the fuzzy logic control system, consists of Fuzzification, Rule based control, Decision making, Defuzification. For this FLC system input are consider as error in rotor speed and change in error in rotor speed. In Fuzification process the inputs are converted into seven linguistic variables show in Fig 7 & 8 .For decision making a sueno method is used with 25 rules.

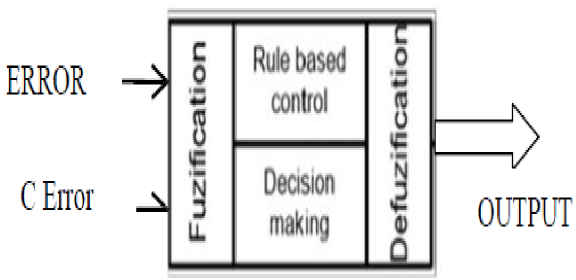

Fig. 6 Fuzzy Logic Control System

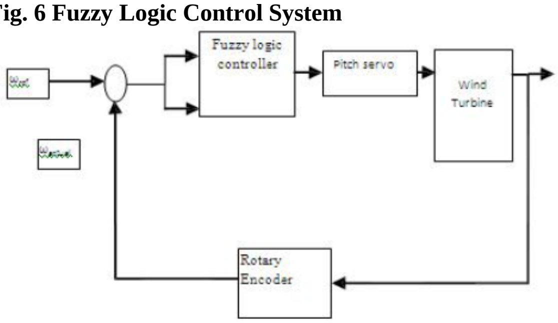

Fig. 7 pitch angle controller

e / de	NL	NM	EZ	PM	PL
NL	PB	PM	PM	PM	PB
NM	PB	PM	PL	PM	PB
EZ	PVB	PM	PVL	PM	PVL
PM	PB	PM	PL	PM	PB
PL	PB	PM	PM	PM	PB

Table.1 Fuzzy Rule Base for current Control

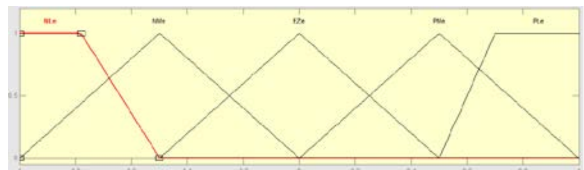

Fig. 8 Rotor speed error

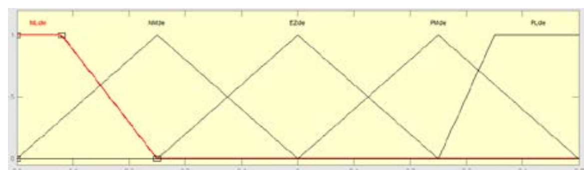

Fig. 9 Change in error in rotor speed

VI. SIMULATION AND RESULTS

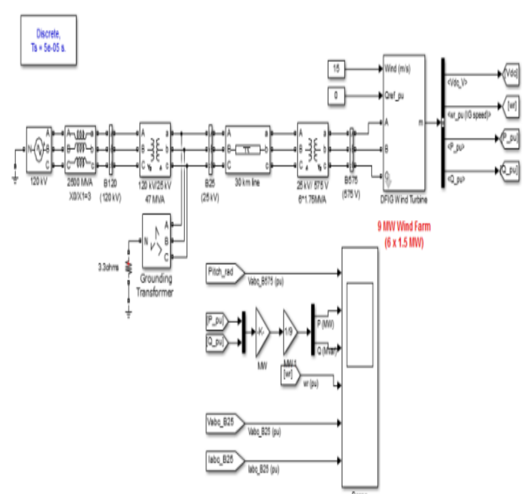

Fig. 10 Simulation of DFIG based wind energy system

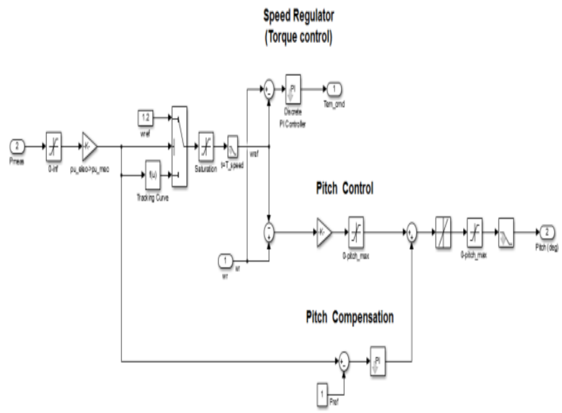

Fig. 11 Simulation of IPC

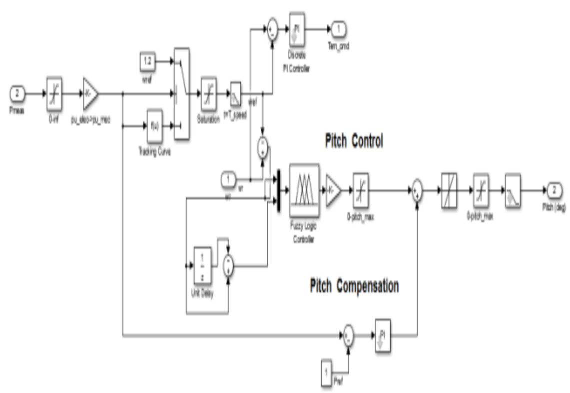

Fig. 12 Pitch angle Control with FLC

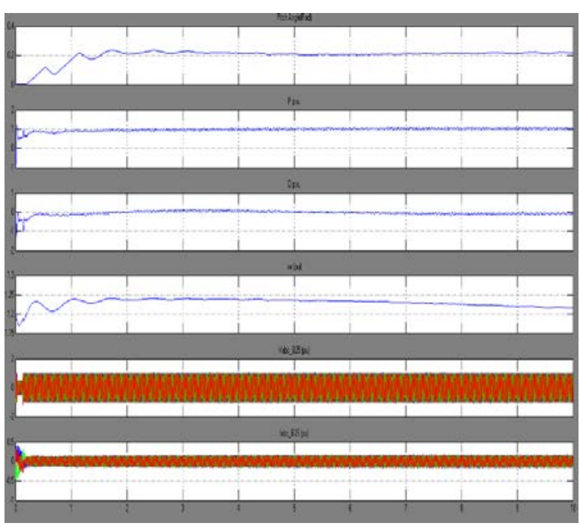

Fig. 13 Pitch angle, Active Power, Reactive Power, Rotor Speed, Grid Voltages and Currents with IPC

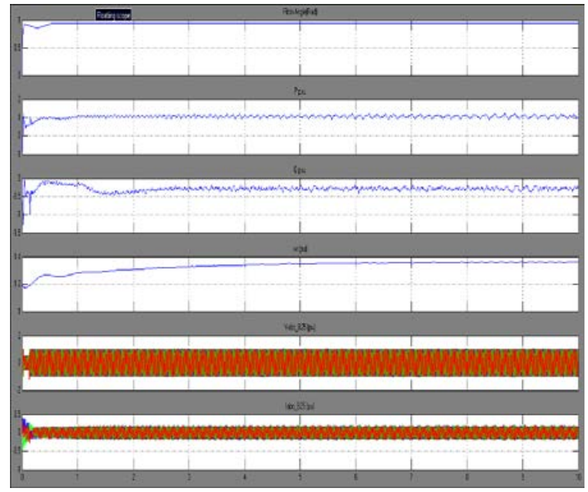

Fig. 14 Pitch angle, Active Power, Reactive Power, Rotor Speed, Grid Voltages and Currents with FLC based Pitch Control

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 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 25 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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