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Implementation of Individual Pitch Control of DFIG Based Variable Speed wind turbines Using Fuzzy Logic for Reduction Flickers

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***Abstract*—Due to the wind speed variation, wind shear and towershadow 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 investi-gate the flicker emission and mitigation issues. An individual pitch control (IPC) strategy is proposed to reduce the flicker emission at different wind speed conditions and also extend, an advanced pitch angle control strategy based on the fuzzy logic is proposed for the variable-speed wind turbine systems. 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.**

***Keywords*—Flicker, flicker mitigation, individual pitch control (IPC), variable speed wind turbine, fuzzy logic**

I. INTRODUCTION

In Recent Years wind power generation is experience a very fast development in the whole world. As the wind power penetration into the grid is increasing quickly, the influence of wind turbines on the power quality is becoming an important issue. One of the power quality aspect 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 [1].

Flicker is defined as "an impression of unsteadiness of visual sensation induced by a light stimulus, whose luminance or spectral distribution fluctuates with time" [2].

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 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 $VR_{\text{rated}}R$, 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].

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],

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 linear zed at the operating points by a small signal analysis. Another scheme using the $H\infty$ controller with a linear matrix inequality approach was proposed, 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 powersource 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 per-formance 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 [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, 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 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 shortenedto 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-agefluctuations 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.

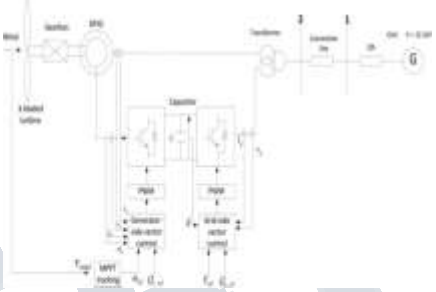

Fig. 1 Overall scheme of the DFIG-based wind turbine

II. 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. In this paper, 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.

B. 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

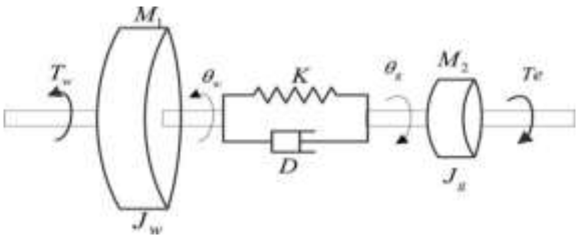

Fig. 2. Two-mass model of the driven train

Which is suitable for transient stability analysis is used. The drivetrain modeling is implemented in FAST.The equations for modeling the drivetrain are given by

$$j_\omega \frac{d^2\Theta_\omega}{dt^2}=T_\omega-D\left(\frac{d\Theta_\omega}{dt}-\frac{d\Theta_g}{dt}\right)-K\left(\Theta_\omega-\Theta_g\right) \quad (1)$$

$$j_g \frac{d^2\Theta_g}{dt^2}=D\left(\frac{d\Theta_\omega}{dt}-\frac{d\Theta_g}{dt}\right)+K\left(\Theta_\omega-\Theta_g\right)-T_e \quad (2)$$

where Jw and 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.

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]:

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

Where is the Power Cp Co-efficient, ρis 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 powerin 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 (λ) and the blade pitch angle (The blade pitch angle can be controlled by using a “pitch-controller” and tip-speed ratio (TSR) is given as

$$\lambda = \frac{wR}{v} \quad (4)$$

Where *w* 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 themechanical 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

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, Eref 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 ωref is obtainedvia 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 andGSC are set to zero to ensure unity power factor operation and reduce the current of RSC and GSC

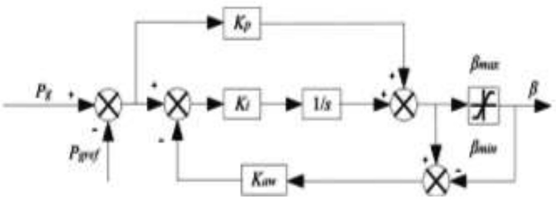

Fig. 4. PI controller with antiwindup

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.

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 bladePitch 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 inFig. 5, the flicker emission will be mitigated effectively if the 3p and higher harmonics of the generator power can be reduced.

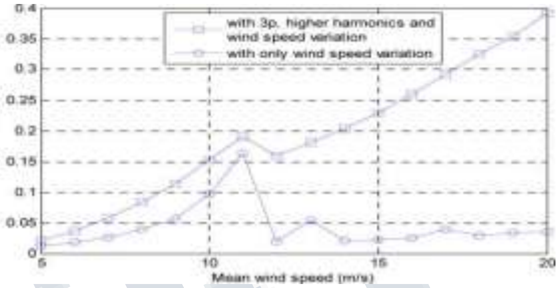

Fig. 5 Flicker severity Pst between the cases with 3p, higher harmonics and wind speed variation (square), and the case with only wind speed variation (circle).

When the wind speed is above the rated wind speed, the pitch angle should be tuned by a traditional collective pitch control (CPC) the output power at its rated value is 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.

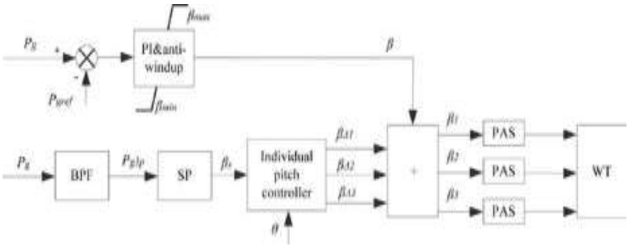

Fig. 6 Proposed individual pitch control scheme

The CPC loop is responsible for limiting the output power. In this loop, Pg ref is the reference generator power 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 Pg3p through and block all other frequencies. Pg3p 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 $\beta\Delta1,\Delta2,\Delta3$ for each blade based on the pitch signal βs and the azimuth angle θ.

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

Table1: Control Principle of Individual Pitch Controller.

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.

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

Where Tpass which is a turbine dependent time constant of the PAS In this case Tpass = 0.1. The control scheme shown in Fig. 6 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 CONTROLLER

In FLC, basic control action is determined by a set of linguistic rules. These rules are determined by the system. Since the numerical variables are converted into linguistic variables, mathematical modeling of the system is not required in FC. The FLC comprises of three parts: fuzzification, interference engine and defuzzification. The FC is characterized as i. seven fuzzy sets for each input and output. ii. Triangular membership functions for simplicity. iii. Fuzzification using continuous universe of discourse. iv. Implication using Mamdani's, 'min' operator. v. Defuzzification using the height method.

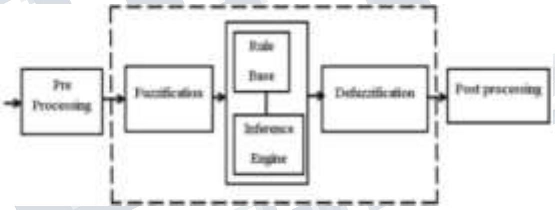

Fig.7: Fuzzy logic controller

Fuzzification: Membership function values are assigned to the linguistic variables, using seven fuzzy subsets: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). The partition of fuzzy subsets and the shape of membership CE(k) E(k) function adapt the shape up to appropriate system. The value of input error and change in error are normalized by an input scaling factor.

Change in error	Error						
	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PM	PM	PS	Z
NM	PB	PB	PM	PM	PS	Z	Z
NS	PB	PM	PS	PS	Z	NM	NB
Z	PB	PM	PS	Z	NS	NM	NB
PS	PM	PS	Z	NS	NM	NB	NB
PM	PS	Z	NS	NM	NM	NB	NB
PB	Z	NS	NM	NM	NB	NB	NB

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Table 2: Fuzzy Rules.

In this system the input scaling factor has been designed such that input values are between -1 and +1. The triangular shape of thememembership function of this arrangement presumes that for any particular *E(k)* input there is only one dominant fuzzy subset. The input error for the FLC is given as

$$E(k) = \frac{P_{ph(k)} - P_{ph(k-1)}}{V_{ph(k)} - V_{ph(k-1)}} \qquad (7)$$

$$CE(k) = E(k) - E(k-1) \qquad (8)$$

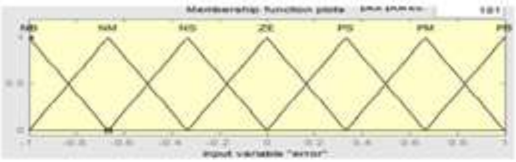

Fig.8 : Membership function

***Inference Method*:** Several composition methods such as Max–Min and Max-Dot have been proposed in the literature. In this paper Min method is used. The output membership function of each rule is given by the minimum operator and maximum operator. Table 2 shows rule base of the FLC

***Defuzzification*:** As a plant usually requires a non-fuzzy value of control, a defuzzification stage is needed. To compute the output of the FLC, „height" method is used and the FLC output modifies the control output. Further, the output of FLC controls the switch in the inverter. In UPQC, the active power, reactive power, terminal voltage of the line and capacitor voltage are required to be maintained. In order to control these parameters, they are sensed and compared with the reference values. To achieve this, the membership functions of FC are: error, change in error and output.

The set of FC rules are derived from

$$u = -[\alpha E + (1-\alpha) * C] \qquad (9)$$

Where α is self-adjustable factor which can regulate the whole operation. E is the error of the system, C is the change in error and u is the control variable. A large value of error E indicates that given system is not in the balanced state. If the system is unbalanced, the controller should enlarge its control variables to balance the system as early as possible.. The set of FC rules is made using Fig.(7) is given in Table 2.

VI. SIMULATION RESULTS

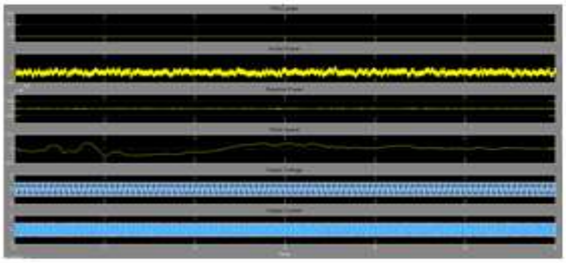

Fig.9: Pitch angle, Grid Voltage, Active Power, Reactive Power, Rotor Speed, Output Voltage, Output Power without IPC.

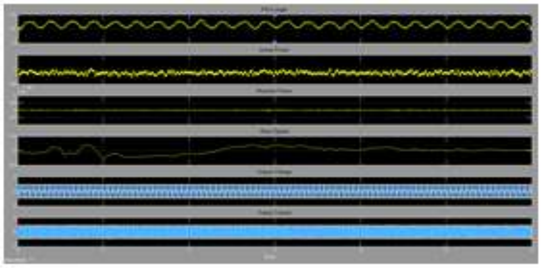

Fig.10: Pitch angle, Grid Voltage, Active Power, Reactive Power, Rotor Speed, Output Voltage, Output Power with IPC.

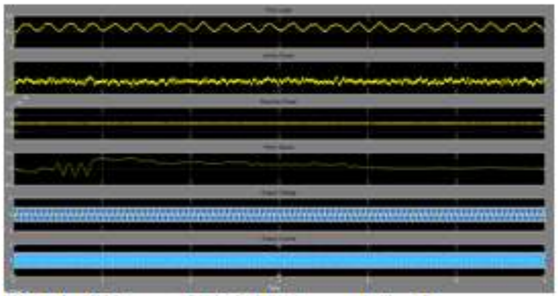

Fig.14: Pitch angle, Grid Voltage, Active Power, Reactive Power, Rotor Speed, Output Voltage, Output Power with FLC.

VI. 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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