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Power Quality Improvement of DFIG using FLC Based Variable Wind Turbines by IPC Method

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Abstract: Because of the wind speed variation, breeze shear along with tower shadow effects, grid connected wind generators are the options for power fluctuations which could produce sparkle during constant operation. This paper presents a type of an MW-level varying speed windmill with a new doubly feasted induction generator to analyze the Flicker emission along with mitigation difficulties. Fuzzy logic controller (FLC) was designed to obtain maximum power extraction at low wind speeds to limit power extraction at 1.5MW nominal power set point. The Fuzzy logic based IPC (Individual Pitch Control) scheme is proposed along with the individual message controller is made using generator active power along the wind turbine. A 1.5MW horizontal axis breeze turbine model was designed for tuning as well as simulation performance is studied and the results show the damping of this generator active power by IPC is an efficient means for flicker minimization of varying speed wind generators during constant operation.

Index Terms: Flicker mitigation, IPC, variable speed wind turbine, DFIG, FLC.

I. INTRODUCTION

During the last few decades, with the growing concerns about energy shortage and environmental pollution, 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[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 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 Inconstant-speed, inconstant-pitch wind turbine systems typically have two operating regions according to the breeze speed. In the partial-load region where the breeze speed is lower than the rated-breeze speed, the turbine speed is controlled at the optimal value so that maximum energy is extracted from the wind turbine. In the full-load region where the wind speed exceeds its rated value, the generator output power is limited at the rated value by the controlling pitch angle since the capacity of the generator and converter are limited.

In practice the majority of wind turbines have pitch control systems with traditional proportional-integral algorithms. These control systems are designed near the nominal wind speeds and power extraction values well as their implementation simplicity. However, the dynamic properties of large wind turbines make them highly non-linear systems. In order to obtain maximum power extraction, non-linear control algorithms are required [6].

This paper presents a Fuzzy control algorithm that gives fine control action. FLC design focuses in gaining a basic understanding of the plant in order to design an appropriate set of rules that can be directly loaded into the fuzzy controller. This is completely opposite to a traditional PI control, where focus is on modeling [7].

II. MODELLING OF WIND TURBINE

A wind turbine model designed with a mechanical turbine (low speed rotors and blades), gear box (multiplicative) and the electrical generator (high speed rotor) as can be shown in fig.1.

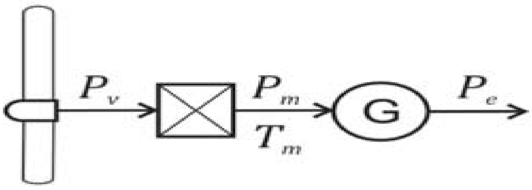

Fig.1 wind turbine model diagram

A breeze turbine is a device designed to extract kinetic energy from the wind .therefore an available wind power is the time derivative of the kinetic energy.

$$P_v = \frac{dK}{dt} = \frac{1}{2}\rho A V^2 \frac{dx}{dt} = \frac{1}{2}\rho A V^3 \ldots (1)$$

This equation represents the amount of energy theoretically available for extraction. However, a limit exists in the extractable energy. This limit is defined as the power coefficient C_p dependent on the wind turbine aero dynamics.

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The maximum C_p available for extraction is known as theBetz limit, and to date, no wind turbine has been able to exceed it. Maximum achievable C_p according to Betz limitis C_p = 0.593[12].

A. Mechanical turbine

The available power from the wind is communicated to the multiplicative gear box. The important aerodynamics aspects that have a specific relationship with the mechanical turbine characteristics can be determined by considering the tip speed ratio coefficient and the λ is defined.

$$\lambda = r w_{tur}/v \text{......... (2)}$$

Where r (rad) is the rotational turbine radius, w_{tur} (rad/sec) is the angular velocity of the mechanical turbine and v is wind speed. The maximum extractable power from the wind power coefficient C_p relation with λ is

$$C_p(\lambda,\beta)=c1\left(\frac{c2}{\lambda}-c3\beta-c4\right)e^{c5/\lambda i}+c6\lambda \text{ ....(3)}$$

And $\frac{1}{\lambda i}=\frac{1}{\lambda+0.08\beta}-\frac{0.035}{\beta 3+1}$

Where c1,c2 .c3,……c7 are specific constants for each wind turbine aerodynamic design. β (degree) is the wind angle of attack at the blade. Here fig .2, shows the C_p -λ curves and table I shows the wind turbine aero dynamics parameters.

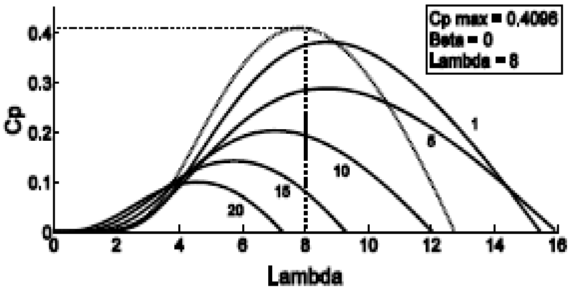


Fig. 2 shows C_p -λ curves for different β of the studied 1.5 MW wind turbine.

Table I Wind turbine Aero dynamic parameters

S.NO	PARAMETER	VALUE
1	B	0,1,2,5,10,20
2	C1	0.516
3	C2	116
4	C3	0.4
5	C4	5
6	C5	21
7	C6	0.08
8	C7	0.035
9	λ	0 to 16

B. Gear box

The gearbox is the mechanical element that multiplies w_{tur} rotational speed of the mechanical turbine into the speed needed for the electric generator ω_m.

The mechanical power Pm delivered at the output of an ideal gearbox as the one considered in this paper is the same as the one extracted from wind and multiplied by the power coefficient C_p,

$$Pm=\frac{1}{2}\rho A V^3 C_p(\lambda,\beta)\text{............ (4)}$$

Therefore, the mechanical power (W) is transmitted to the electrical generator with the following expression of mechanical torque.

$$T_m = P_m/w_m \text{ .... (5)}$$

C. Mechanical drive train

The effects of generator and drive train on the breeze turbine of mechanical rotation of two-mass model as shown in fig.3, suitable for transient stability analysis are used.

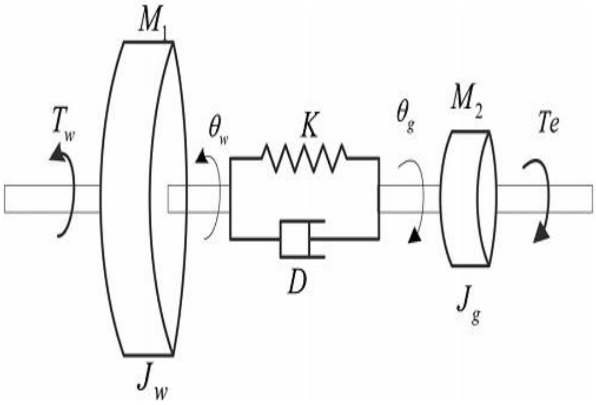


Fig.3.Two-mass model of the drive train

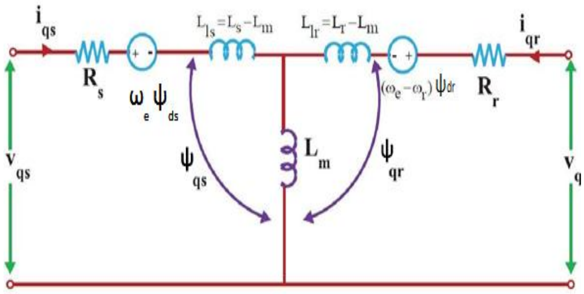
$$T_w = M_1\frac{d^2\theta w}{dt^2}+k(\theta_\omega-\theta_g)+D\left(\frac{d\theta w}{dt}-\frac{d\theta g}{dt}\right)$$

$$\text{.........\,.\,.\quad (6)}$$

$$T_e = M_2\frac{d^2\theta g}{dt^2}+k(\theta_g-\theta_w)+D\left(\frac{d\theta g}{dt}-\frac{d\theta w}{dt}\right)\text{........ (7)}$$

D. Electrical Equivalent Circuit of DFIG

The equivalent circuit diagram of an induction machine is shown in Fig.4 In this figure the machine is represented as two phase machine, it has already been discussed before that a three phase machine can be represented as two phase machine obeying certain rules. For the modelling of DFIG in synchronously rotating frame we need to represent the two phase stator (d^s-q^s) and rotor (d^r-q^r) circuit variables in a synchronously rotating (d-q) frame.



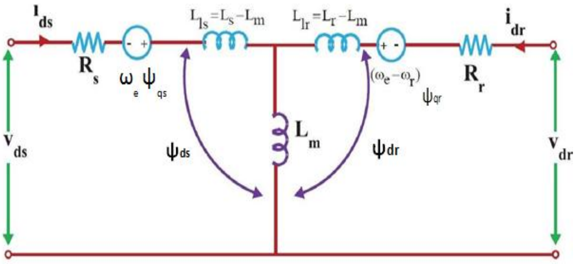


Fig.4.,d−q equivalent circuit of DFIG at synchronously rotating reference frame.

The stator circuit equations are

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\varphi_{qs} - \omega_e \varphi_{ds} \text{............} (8)$$

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\varphi_{ds} - \omega_e \varphi_{qs} \text{..........} (9)$$

Where all the variables are synchronously rotating frame. The bracketed terms are defined as the back e.m.f.

Similarly the rotor cicuit the machine equations are can be written as

$$V_{qr} = R_r i_{qr} + \frac{d}{dt}\varphi_{qr} + \omega_e \varphi_{dr} \text{..........} (10)$$

$$V_{dr} = R_r i_{dr} + \frac{d}{dt}\varphi_{dr} - \omega_e \varphi_{qr} \text{...........} (11)$$

All the parameters are referred to the primary circuit, which is a stator in this case. Let the rotor rotates at an angular speed ω_r, then the d-q axes fixed on the rotor fictitiously will move at a relative speed ω_e-ω_r to the synchronously rotating frame.

$$V_{qr} = R_r i_{qr} + \frac{d}{dt}\varphi_{qr} + (\omega_e - \omega_r)\varphi_{dr} \text{....} (12)$$

$$V_{dr} = R_r i_{dr} + \frac{d}{dt}\varphi_{dr} - (\omega_e - \omega_r)\varphi_{qr} \text{....} (13)$$

The flux linkage expressions in terms of current can be written from Fig.4. as follows:

$$\varphi_{qs} = L_{1s} i_{qs} + L_m(i_{qs} + i_{qr}) = L_s i_{qs} + Lm i_{qr} \text{...} (14)$$

$$\varphi_{ds} = L_{1s} i_{ds} + L_m(i_{ds} + i_{qr}) = L_s i_{ds} + Lm i_{dr} \text{..} (15)$$

$$\varphi_{qr} = L_{1r} i_{qr} + L_m(i_{qs} + i_{qr}) = L_r i_{qr} + Lm i_{qs} \text{...} (16)$$

$$\varphi_{dr} = L_{1r} i_{dr} + L_m(i_{ds} + i_{dr}) = L_r i_{dr} + Lm i_{ds} \text{...} (17)$$

$$\varphi_{qm} = L_m(i_{qs} + i_{qr}) \text{.........} (18)$$

$$\varphi_{qm} = L_m(i_{qs} + i_{qr}) \text{.........} (19)$$

The electrical speed ω_r cannot be treated as constant in the above equations. It can be connected to the torque as

$$T_e = \frac{3}{2} p \frac{L_m}{L_s} \Psi_s i_{qr} \text{..........} \quad (20)$$

$$Pe = -\frac{3}{2} u_s \frac{L_m}{L_s} i_{qr} \text{...........} (21)$$

III. WIND TURBINE CONTROL AND FLICKER EMISSION

For the DFIG-based variable swiftness wind mill, the command target takes a different approach as outlined by diverse wind swiftness. Inside reduced wind swiftness; the command goal should keep your tip speed ratio ideal, so that the maximum strength is usually captured in the wind. Inside high wind swiftness, because of readily available strength in the wind mill. The potential may clog the machine, and this command target should be to keep you to produce constant strength from their ranked price.

A. Conventional PI controller

A Proportional-Integral control is a special case of family known as proportional-Integral-Derivative (PID). This type of controllers are most common way of controlling industry process in a feedback configuration [10,11].

For the desired PI controller for the 1.5 MW wind turbine error signal was

$$e(t) = P_{ed}(t) - P_e(t) \text{.......}(22)$$

Where, P_{ed} is the desired output power or set point for the wind turbine. In this case of 1.5 MW, P_e is the actual delivered power from the wind turbine [6].

The PI control was optimized to achieve rapid response to different wind speed changes and to deliver nominal power output for nominal wind speed (*11.75 m/s*) as well as higher wind speeds. The fig.5. shows a closed loop analysis was performed at an operating mode for nominal wind speed and without altered aerodynamic blade pitch conditions (*v = 11.75 m/s, β = 0º*).The Ziegler – Nichols tuning method was then applied to obtain initial gains, which were modified on a trial and error basis to obtain a desirable response. Obtained gains were: KP = 4.65 and Ki = 46.5.

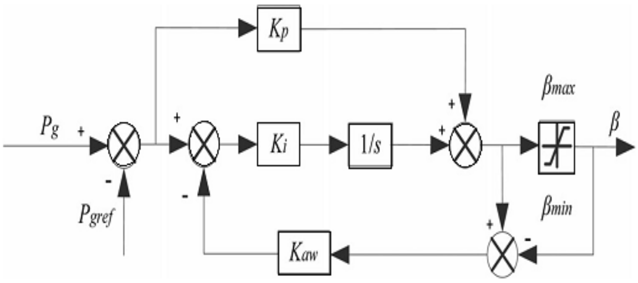


Fig.5. PI control system

B. flicker emission in normal operation

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. PROPOSED FLC BASED IPC FOR FLICKER MITIGATION

Fuzzy modelling is the method of describing the characteristics of a system using fuzzy inference rules. The method has a distinguishing feature in that it can express linguistically complex non-linear system. It is however, very hand to identify the rules and tune the membership functions of the reasoning. Fuzzy Controllers are normally built with fuzzy rules. These fuzzy rules are obtained either from domain experts or by observing the people who are currently doing the control[13].

The membership functions for the fuzzy sets will be derive from the information available from the domain experts and/or observed control actions. The building of such rules and membership functions require tuning. That is, performance of the controller must be measured and the membership functions and rules adjusted based upon the performance. This process will be time consuming.

The basic configuration of Fuzzy logic control based as shown in Fig. 6.,consists of four main parts i.e. (i) Fuzzification,(ii) knowledge base, (iii) Inference Engine and (iv) Defuzzification.

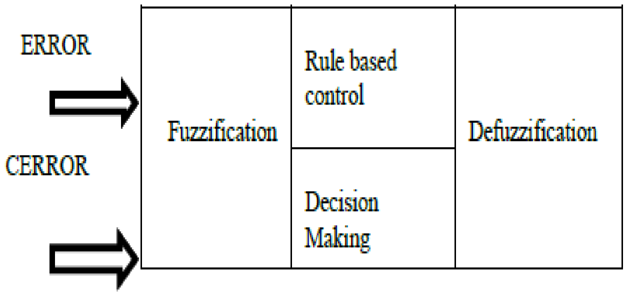


Fig.6. Structure of Fuzzy Logic controller

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 fuzzy 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. 6, in which the anti wind up 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 anti windup feedback term is zero.

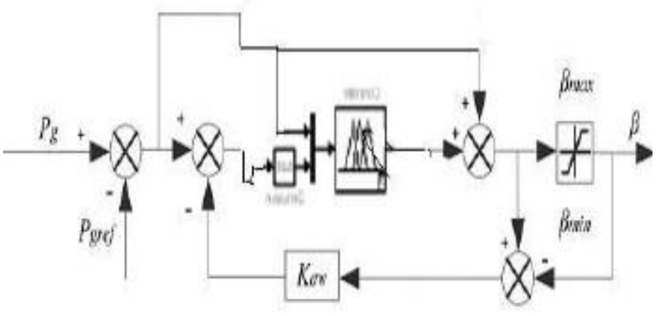


Fig.7.Fuzzy controller with antiwindup.

This section concentrates on flicker mitigation of variable speed 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 FLC Based IPC strategy is proposed. The control scheme is shown in Fig. 8. The control scheme consists of two control loops: CPC loop and IPC loop.

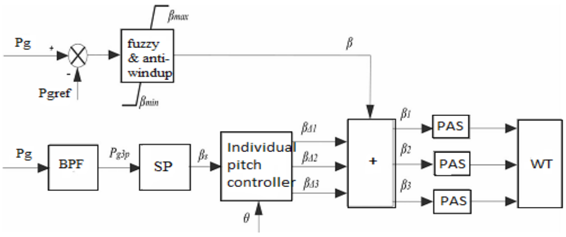


Fig.8. Proposed FLC Based Individual pitch control scheme.

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, $\beta$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

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increment for a specific blade[13]. 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 onthe 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. For example, if the azimuth angle belongs to the area of (0, 2 π/3), then $\beta\Delta2$ equals βs, 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 is usually represented by using a first-order transfer function:

$$F(s)=\frac{1}{T_{pas}s+1} \quad \text{……….. (23)}$$

Where Tpas which is a turbine dependent time constant of the PAS. In this case Tpas = 0.1 The control scheme shown in Fig.4.4 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[16].

TABLE:II Postscript Specifications of a breeze Turbinee with DFIG

S.NO	DFIG AND BREEZE TURBINE	CAPACITY
1	Rated capacity(MW)	1.5
2	Rated stator voltage(V)	690
3	Rated frequency(HZ)	50HZ
4	Stator resistance(Ω)	0.0968
5	Resistance of rotor(Ω)	0.0003808
6	Leakage inductance of a stator (H)	0.0003808
7	Leakage inductance of a rotor(H)	0.000048
8	Magnetizing inductance(H)	4.68
9	Blade radius(m)	0.35
10	Number of poles	4
11	Inertia constant (s)	3.0
12	Number of blades	3
13	Gear box ratio %	81

V.SIMULATION STUDIES USING FUZZY IPC

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 Fuzzy Based IPC method..Fig9.,shows the simulation diagram with FLC ,and the simulation results of the long-term view of the generator active power the mean wind speed is above the rated wind speed and voltages &currents, pitch angles wave forms using PI, With IPC using Fuzzy as shown from fig. 10 to fig.15 It is shown that the generator active power to the grid is smoothed prominently.

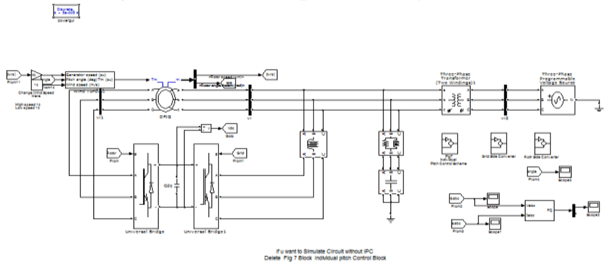

Fig .9.simulation diagram

VI. SIMULATION RESULTS

A. *Proposed FLC Based Individual Pitch Controller (IPC)*

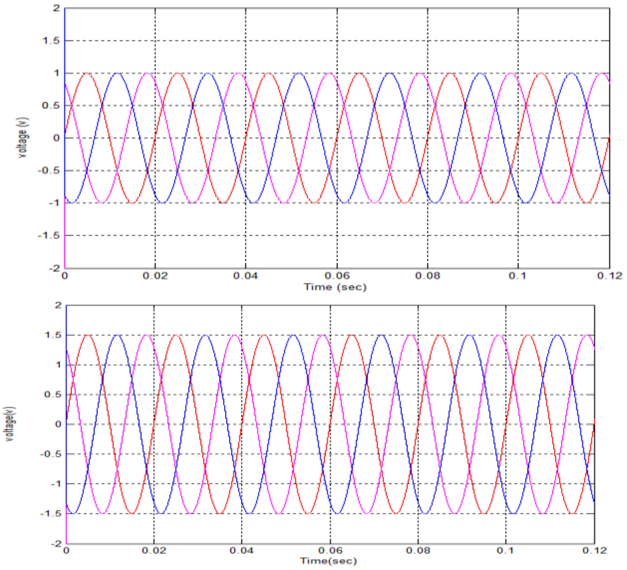

Fig. 10 Performance of generated voltage with IPC using PI and Fuzzy controller Respectively

At wind speed 12 m/s

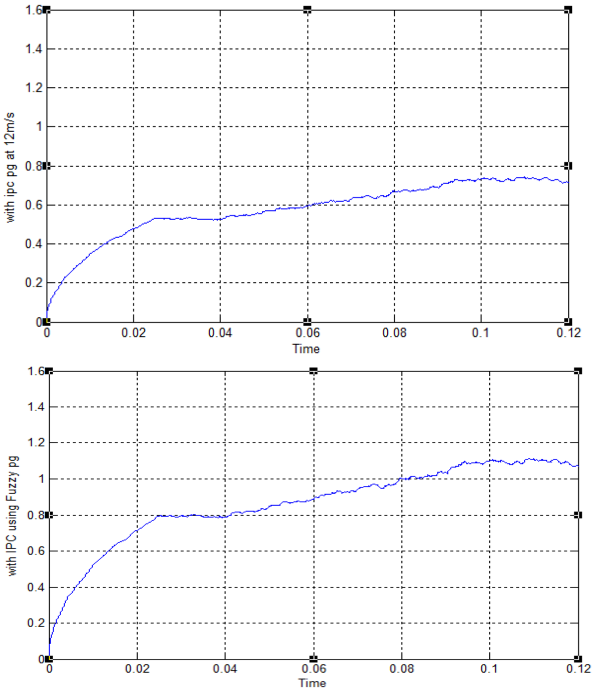

Fig. 11 Performance of Generator Active power Pg with IP Cusing PI and Fuzzy controller Respectively

At wind speed 14 m/s

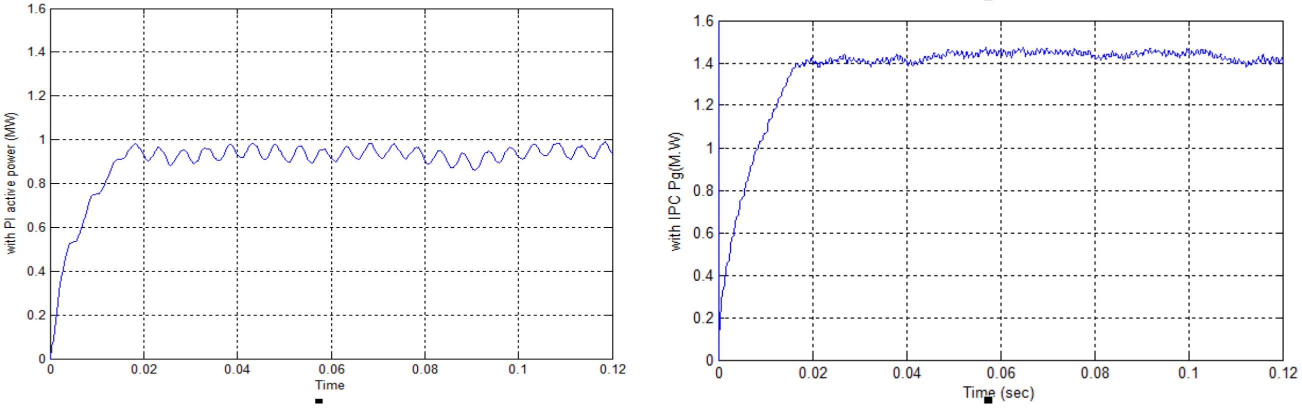

Fig. 12 Performance of Generator Active power Pg with IPC using PI and Fuzzy controller Respectively

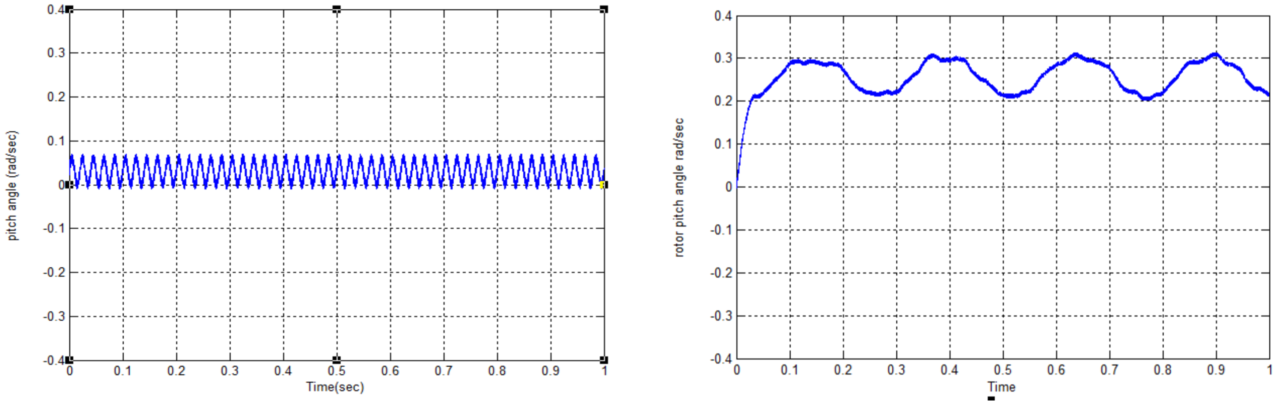

Fig .13 Performance of pitch angle with IPC using PI and Fuzzy controller respectively

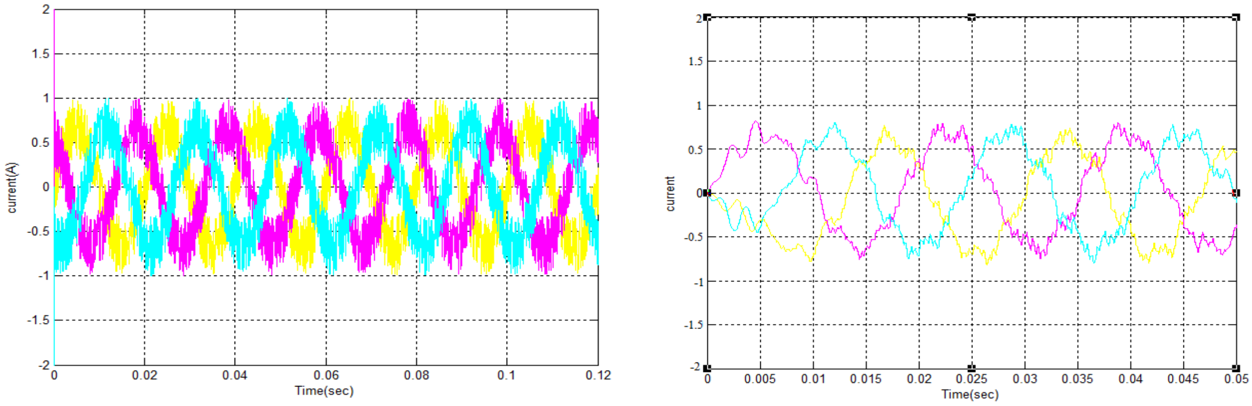

Fig. 14 Performance of generated current with IPC using PI controller and with IPC using Fuzzy controller

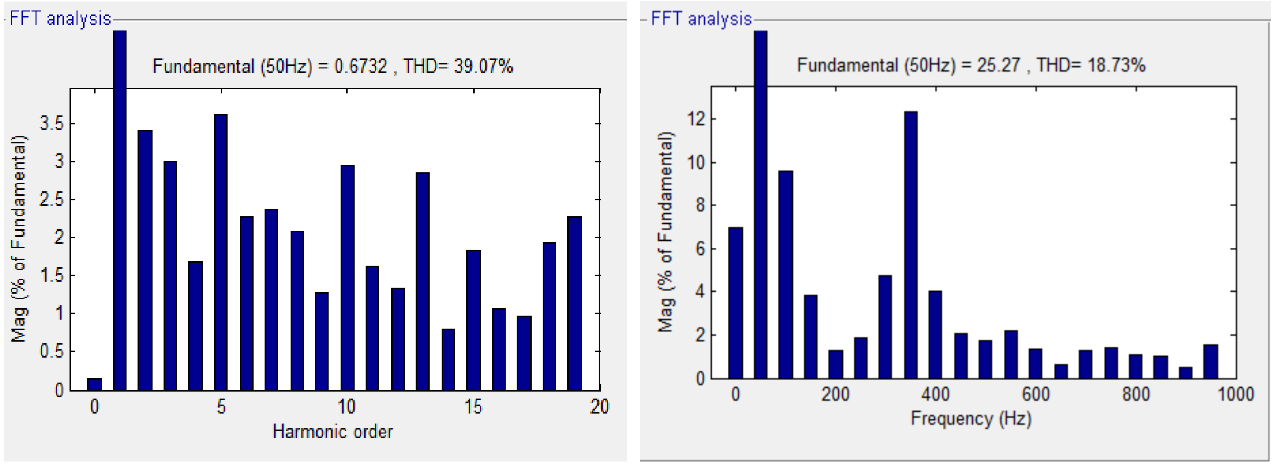

Fig. 15 Performance of current THD% with IPC using PI(39.07) controller and with IPC using Fuzzy(18.73) controller

COMPARISON OF RESULTS:

S.NO	SPEED In m/S	CONTROLLER	POWER In MW
1	12 m/s	With PI	0.78
		with fuzzy	1.16
2	14 m/s	With PI	1.01
		with fuzzy	1.41

VII. CONCLUSION

This paper describes a flicker mitigation by simply IPC connected with variable-speed wind turbines with MW-level DFIG. The modeling with the wind turbine system is accomplished using FAST and Simulink. On suchbasis as the presented model, flicker emission can be analyzed and investigated in numerous mean the wind speeds. To relieve the flicker emission, any novel handle scheme by simply IPC can be proposed. The generator active power oscillation that leads to flicker emission can be damped prominently by the FLC-IPC with both large and minimal wind data transfer rates. It could be concluded on the simulation final results that damping the actual generator energetic power oscillation by simply Fuzzy Controlled Based IPC is definitely an effective means intended for flicker mitigation connected with variable speed wind turbines during continual operation.

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