CONTROLLING FLICKER CAUSED DUE TO POWER FLUCTUATIONS BY USING INDIVIDUAL PITCH CONTROL FOR A VARIABLE SPEED DFIG BASED WIND TURBINE

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Abstract – *Energy demands of the world are enormously increasing. In this scenario the non renewable sources play an important role in meeting the energy needs. Wind energy have a lot of potential for generating large amounts of energy with zero input cost and no by products. Therefore it is very important to maintain the power quality while generating the power through wind turbine. In this paper IPC control scheme is proposed a new scheme to reduce the power fluctuations which are responsible for reduction of the generated power quality. This scheme is applicable to MW – level DFIG based variable speed wind turbine.IPC scheme uses the active power generated and azimuth angle of blade as reference for reduction of flicker.IPC along with FLC reduces the oscillates in active power generated to a great extent. The proposed scheme is designed and implemented in MATLAB/Simulink.*

Key Words: **Flicker, flicker mitigation, individual pitch control (IPC), variable speed turbine, collective pitch control(CPC), fuzzy logic controller(FLC)**

1. INTRODUCTION

Presently the reality vitality interest may be expanding because of number development and up to date modern culture persuading a considerable measure of ventures done elective vitality wellsprings for example, Solar, Wind, bio-mass, energy units etc; "around the renewable vitality sources, wind vitality reliably demonstrates its great possibility to serve Similarly as clean What's more boundless vitality wellspring. For the increment about wind control infiltration under the grid, the energy caliber gets to be a critical issue. You quit offering on that one essential part from claiming force nature may be flicker since it might turn into a restricting component for coordination wind turbines under feeble grids, Furthermore actually under generally solid grids assuming that the wind force infiltration levels are secondary. Flicker is characterized as "an feeling of precariousness for visual sensation prompted Toward a light stimulus, whose luminance or ghastly conveyance oscillates with time". Flicker may be prompted toward voltage fluctuations, which need aid initiated by load stream transforms in the grid. Grid-connected variable velocity wind turbines are fluctuating force sources Throughout constant operation. The force variances created by wind pace variation, wind shear, tower shadow, yaw errors, and so on. , prompt those voltage variances in the network, which might transform flicker. Separated from the wind control wellspring conditions, the control framework aspects likewise bring effect on flicker emanation about grid-connected wind turbines, for example, such that impede ability Furthermore grid impedance point. The flicker emanation for diverse sorts for wind turbines will be exactly different. In spite of variable-speed wind turbines are better regarding 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.

Previously there are number of ways to reduce the flicker in power generated. These are implemented by using reactive compensation. When the grid has a very low impendence angle ie 10^0 these techniques will be redundant. For a large distributive networks the reactive power needed for compensation will be as greater as 3.26pu which is practically not possible to generate from STATCOM especially when DFIG is present in the system. Another way by controlling the active power by varying the DC link capacitance can be used for reducing flicker but this requires a large capacitance which is of high cost and reduces the life of capacitor in storing the energy. Pitch actuating system can also be used for mitigation of flicker but time delay and pitch rate great affects the system. This affect is considerably large in case of variable speed turbines.

As a result of above mentioned drawbacks of existing solutions there is a need to find an alternative solution for power fluctuation mitigation. A novel scheme used in helicopter industry for load reduction is applied to wind turbine. That is pitching the blades individually as per the wind speed and direction of wind flow.IPC is a promising solution for reducing power oscillation in active power generation in case of distributive network systems.

2. 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, FIG, 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, MATALB 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. Maximum power tracking is achieved by implementing vector control strategy through which the inputs to the generator can be controlled as per the wind speeds. At very low speeds the trapping of wind power is preferred and at high speeds prevention of dangerous speeds of wind turbine can be achieved.

The convertors of RSC and GSC are designed by using IGBTs.

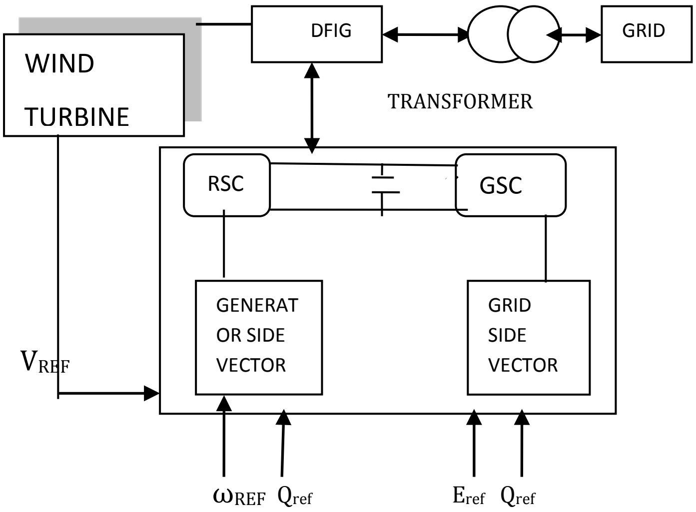


Fig 1 Overall schematic diagram of wind turbine system

3. MECHANICAL DRIVE TRAIN
4.

In order to take into account the effects of the generator and drive train on the wind turbine, two-mass model is shown below

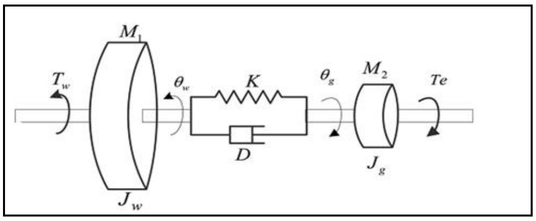


Fig 2 Two mass model of drive train

The equations for modeling the drive train are given by

$$J_\omega \frac{d^2\theta_\omega}{dt^2} = T_\omega - D\left\lfloor \frac{d\theta_\omega}{dt} - \frac{d\theta_g}{dt} \right\rfloor - K(\theta_\omega - \theta_g)$$

$$J_g \frac{d^2\theta_g}{dt^2} = D\left\lfloor \frac{d\theta_\omega}{dt} - \frac{d\theta_g}{dt} \right\rfloor + K(\theta_\omega - \theta_g) - T_e$$

Where J_ω and J_g are the moment of inertia of wind turbine and generator, respectively T_ω,T_e are the wind turbine torque and generator electromagnetic torque, respectively, θ_ω,$\theta_g$are the mechanical angle of wind turbine and generator, K is the drive train torsion spring, D is the drive train torsion damper.

4. MODELING EQUATIONS OF DFIG

4.1 DFIG equivalent circuit

The DFIG modeling can be done by using the equivalent circuit as shown below.

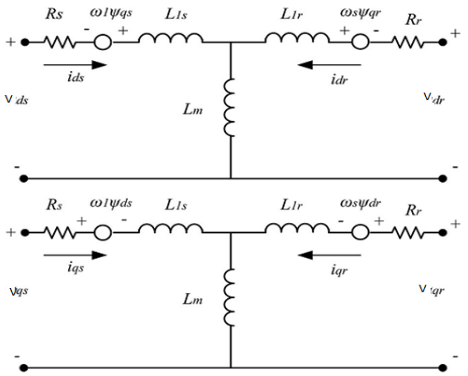


Fig 3 Equivalent circuit of DFIG

The torque active and reactive power equations are given below which showns active power can be controlled by varing q axis flux and reaction power can be controleed by d axis flux

$$T_e = \frac{3}{2} P \frac{L_m}{L_s} \psi_s I_{qr}$$

$$P_s = -\frac{3}{2} u_s \frac{L_m}{L_s} I_{qr}$$

$$Q_s = \frac{3}{2} \frac{\psi_s}{L_s} u_s - \frac{3}{2} u_s \frac{L_m}{L_s} I_{dr}$$

Where P is number of poles. From above equations we can say active and reactive power are controlled by I_{qr} and I_{dr}

4.2Dynamic model of DFIG

In order to investigate the actual behavior of the DFIG, dynamic equation needs to be considered for more realistic observation. From the point of view of the control of the machine, the *d-q* representation of an induction machine leads to control flexibility. The dynamic behavior of the DFIG in synchronous reference frame can be represented by the Park equations provided all the rotor quantities are referred to the stator side.

The stator and rotor voltages are expressed as follows:

$$V_{ds} = R_s I_{ds} + \frac{d\phi_{ds}}{dt} - \omega_s \phi_{qs}$$

$$V_{qs} = R_s I_{qs} + \frac{d\phi_{qs}}{dt} - \omega_s \phi_{ds}$$

$$V_{dr} = R_r I_{dr} + \frac{d\phi_{dr}}{dt} - (\omega_s - \omega_r)\phi_{qr}$$

$$V_{qr} = R_r I_{qr} + \frac{d\phi_{qr}}{dt} + (\omega_s - \omega_r)\phi_{qs}$$

The flux linkage equations of the stator and rotor can be related to their currents and are expressed as follows:

$\phi_{ds} = L_{ss}I_{ds} + L_m I_{dr}$
$\phi_{qs} = L_{ss}I_{qs} + L_m I_{qr}$
$\phi_{dr} = L_{rr}I_{dr} + L_m I_{ds}$
$\phi_{qr} = L_{rr}I_{qr} + L_m I_{qs}$

Where $L_{ss} = L_s + L_m$ and $L_{rr} = L_r + L_m$

The electromagnetic torque developed by the DFIG is related to the torque supplied by the turbine and can be expressed as

$$T_e = 1.5P\left[\phi_{ds}I_{qs} - \phi_{qs}I_{ds}\right]$$
$$=2\text{H}\left[\frac{d\omega_m}{dt} + B\omega_m + T_m\right]$$

Where, T_m is positive for motoring operation and negative for generator operation. Equations are the set of differential equations which represent a fourth order model for describing the dynamic behavior of DFIG.

5.CONTROLLING SCHEMES FOR CONVERTERS ON STATOR AND ROTOR SIDE OF DFIG

Vector control technique is used for controlling the gate pulses of the converters used on stator side and rotor side. 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_{sref}. 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

5.1 Vector control strategy

Stator flux oriented vector scheme is adopted for achieving decoupled control of active and reactive power control. Following assumptions are assumed in vector control strategy

- Stator voltage drop across resistance has been neglected as the effect of stator resistance is quite low compared to the grid voltage.
- The DFIG is connected to a stiff grid, i.e., the frequency and amplitude of the stator or grid voltage is assumed constant.
- Magnetizing current of the stator is assumed to be determined by the grid.
- The q-axis is 90^0 ahead of the d-axis and rotating at synchronous speed in the direction of rotation.
- The stator flux vector is aligned with the d-axis of the stator.

The above assumptions lead to the following

$V_{ds} = 0$ & $\phi_{ds} = \phi_s$
$V_{qs} = V_s$ & $\phi_{qs} = 0$

Neglecting the stator resistance, i.e. $R_s = 0$ stator and rotor voltage equations will be

$V_{ds} = 0 = \frac{d\phi_{ds}}{dt} - \omega_s\phi_{qs}$
$V_{qs} = \omega_s\phi_{ds} = V_s = \frac{d\phi_{qs}}{dt} + \omega_s\phi_{ds}$
$V_{dr} = R_r I_{dr} + \frac{d\phi_{dr}}{dt} - (\omega_s - \omega_r)\phi_{qr}$
$V_{qr} = R_r I_{qr} + \frac{d\phi_{qr}}{dt} - (\omega_s - \omega_r)\phi_{dr}$

Also

$\phi_{ds} = L_{ss}I_{ds} + L_m I_{dr}$
$0 = L_{ss}I_{qs} + L_m I_{qr}$
$\phi_{dr} = L_{rr}I_{dr} + L_m I_{ds}$
$\phi_{qr} = L_{rr}I_{qr} + L_m I_{qs}$

The rotor voltages are obtained as

$V_{dr} = R_r I_{dr} + \left[L_{rr} - \frac{L_m^2}{L_{ss}}\right]\frac{dI_{dr}}{dt} - (\omega_s - \omega_r)\left[\left(L_{rr} - \frac{L_m^2}{L_{ss}}\right)\right]I_{qr}$
$V_{qr} = R_r I_{qr} + \left[L_{rr} - \frac{L_m^2}{L_{ss}}\right]\frac{dI_{qr}}{dt} - (\omega_s - \omega_r)\left[\left(L_{rr} - \frac{L_m^2}{L_{ss}}\right)\right]I_{dr} - \frac{L_m V_s}{\omega_s L_{ss}}$

The active and reactive power produced in stator and rotor fluxes are

$P_s = \frac{-L_m}{L_{ss}}V_s * I_{qr}$
$Q_s = \frac{V_s^2}{\omega_s L_{ss}} - \frac{V_s L_m}{L_{ss}} * I_{dr}$

6.FLICKER MITIGATION SCHEMES

6.1 Collective 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 below, in which the anti windup 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 anti windup feedback term is zero.

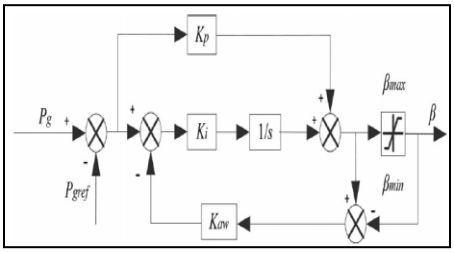


Fig 4 Block diagram of PI controller

7.CPC AND IPC CONTROL SCHEMES

7.1Cyclic pitch control modeling equations

For attenuating loads the most simple method is especially those caused at 1P frequencies is CPC. The basic principle of cyclic pitch control is given by Larsen as “Measure mean tilt rotor and yaw moments and compensate by an aerodynamic moment created by a cyclic pitch variations that are 120◦ out of phase (3 bladed machine)”. In this method the rotating blade flap and edge wise blade root moments are converted into non rotating rotor coordinates as given in below equations

$$M_{x,i}^{R} = M_{x,i}^{B}\cos(\theta_i) + M_{y,i}^{B}\sin(\theta_i)$$

$$M_{tilt} = \sum_{i=1}^{B} M_{x,i}^{R}\cos(\phi_i)$$

$$M_{yaw} = \sum_{i=1}^{B} M_{x,i}^{R}\sin(\phi_i)$$

where $M_{x,i}^{R}$ and $M_{y,i}^{B}$ are the flap and edgewise blade root bending moments of blade i, with ψ_i being the azimuth angle of the respective blade i and θ_i is the pitch angle of the blade. M_{tilt} andM_{yaw} represent the tilt and yaw moments at the rotor centre. Then these moments are compensated and the resulting pitch action is a combination of θ yaw and θ tilt given by

$$\theta_{cyc,i} = \theta_{tilt}\sin(\phi_i + \phi) + \theta_{yaw}\cos(\phi_i + \phi)$$

When wind speeds are below rated power, typically below 12 m/s, the rotor blades are turned fully towards the wind which means that the pitch is positioned at 0°. At increasing wind speeds the pitch of the blades is controlled in order to limit the power output of the turbine to its nominal value. When wind speeds reach a predefined threshold, typically 28 m/s, the turbine stops power production by turning the blades to a 90° position. Collective pitch control adjusts the pitch of all rotor blades to the same angle at the same time.

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.

7.2Modeling of IPC

The IPC control scheme consists of four main blocks. They are Band pass filter (BPF), signal processor (SP), individual pitch controller (IPC) and pitch actuation system (PAS). The transfer functions and design parameters of each block are discussed below

7.2.1 Design of BPF

The transfer function of BPF is

$$F(s) = \frac{K_S}{S^2 + \frac{\omega_C}{Q}s + \omega_c^2}$$

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 .

$$\omega_c = \frac{3\omega_g}{N}$$

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 $Q = \omega_c$.

7.2.2 Signal processing block

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 power transfer 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 P_{g3p} . 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 with3p 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:

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

The angle contribution is

$$\delta(\omega) = -arc\ \tan(\omega T_{sp})$$

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

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

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

Table 1 Control principle of Individual Pitch Controller

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

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 in such a way that 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 $\beta_{\Delta2}$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 can be represented using a first-order transfer function:

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

Where T_{pas} which is a turbine dependent time constant of the PAS. In this case *Tpas=0.1*. The control scheme 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.

7.3 Block diagram of IPC and CPC control schemes

For control of wind turbine, a novel IPC strategy is proposed. The control scheme consists of two loops; CPC loop and IPC loop.

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 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 for increase of pitch for a specified blade

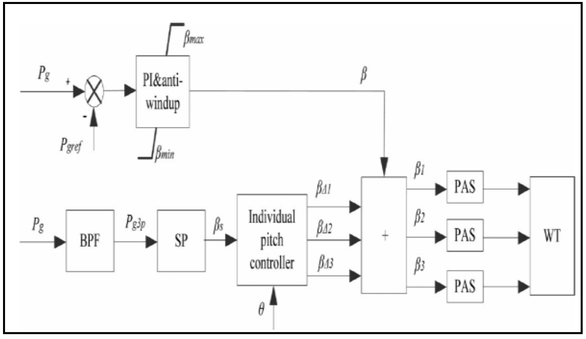


Fig 5 Proposed IPC scheme block diagram

7.4Fuzzy logic controller

In this paper fuzzy logic controller is also used for pitching the blades effectively.FLC is used along with IPC scheme for an effective control of power fluctuations. Fuzzy logic table is designed accordingly as per the requirements of wind turbine. As linguistic variables are used in FLC it is easy to design and develop the FLC modeling in MATLAB.Below table shows the implementation of fuzzy logic in DFIG based wind turbine for controlling power fluctuations.

		ERROR				
		VB	SB	OP	SL	VL
WIND SPEED	BL	PB	PS	Z	Z	Z
	SL	PB	PS	Z	Z	Z
	OP	PB	PS	Z	Z	Z
	SH	PB	PS	PS	PS	PS
	BH	PB	PB	PB	PB	PB

Table 2 Fuzzy logic implementation

8.MATLAB MODELING AND SIMULATION RESULTS

Modeling is done using MATLAB simulink.the MATLAb blocks are shown below

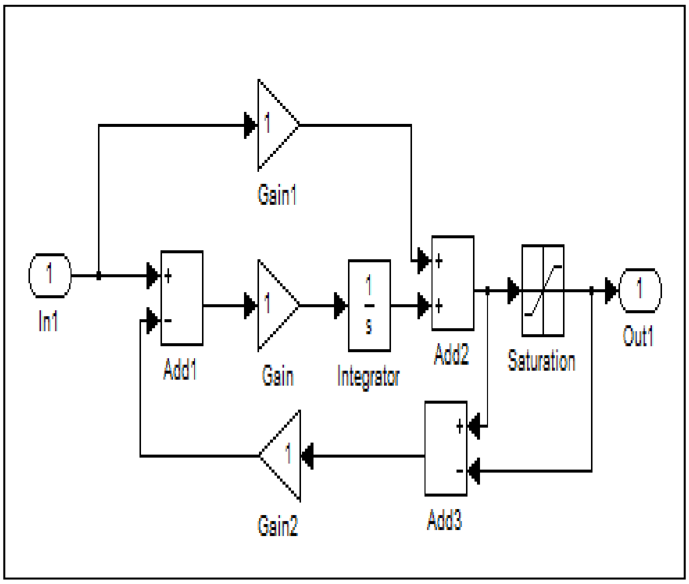


Fig 6 Modeling of Collective pitch control

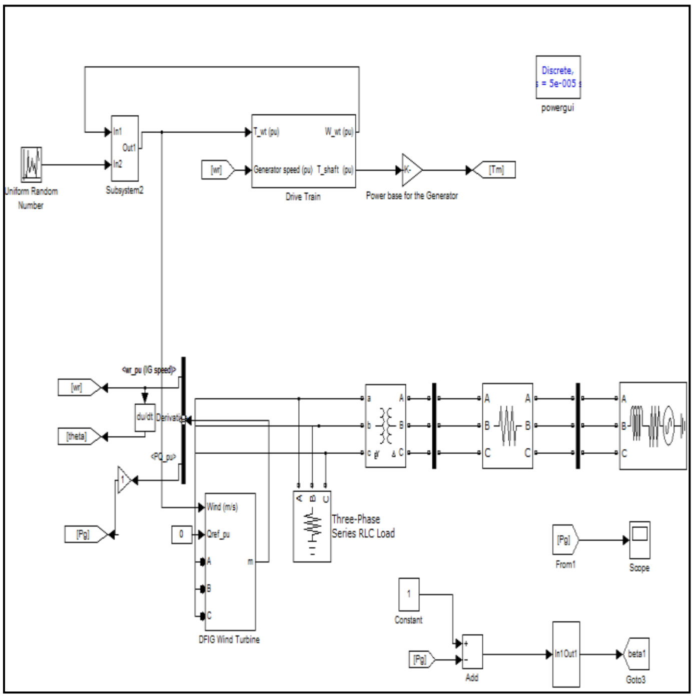


Fig 7 Wind turbine modeling with CPC

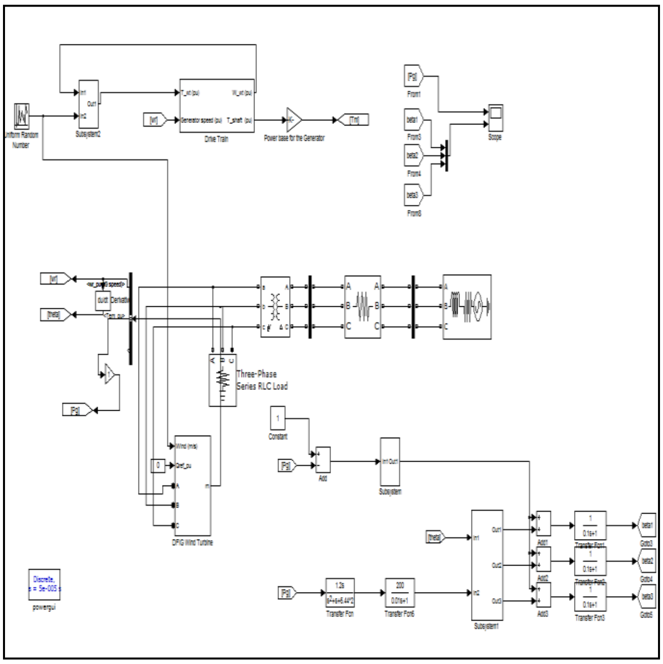


Fig 8 Modeling of wind turbine with IPC control scheme

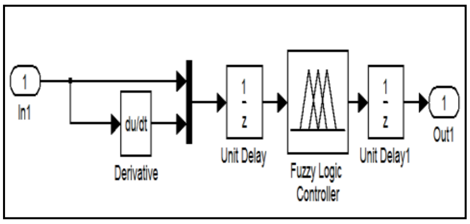
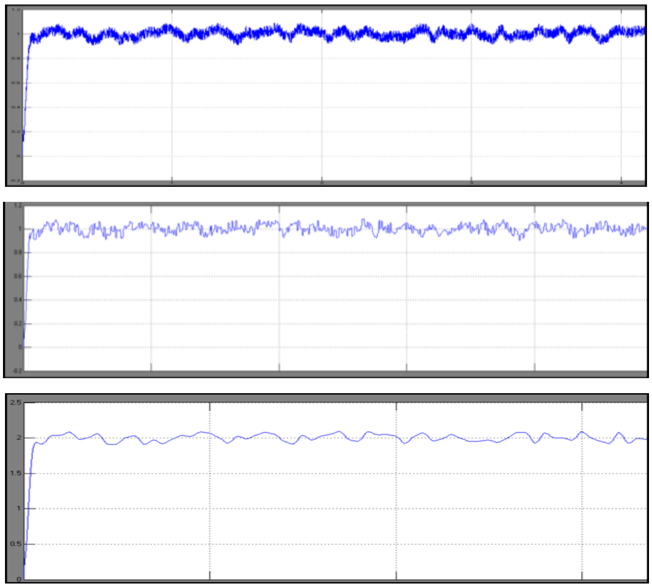
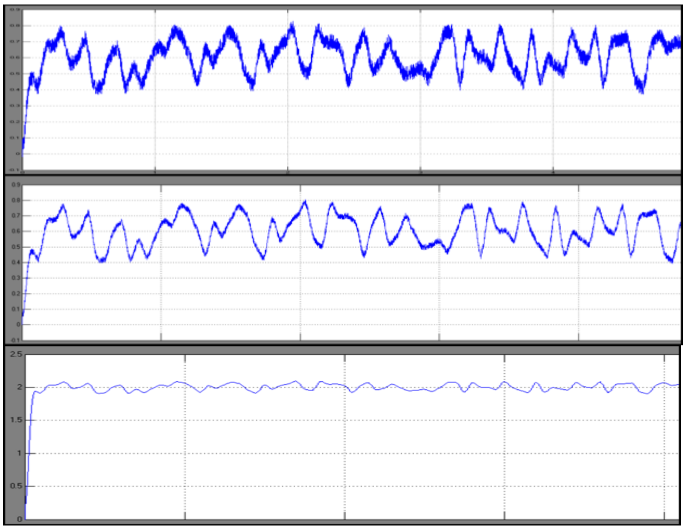


Fig 9 Modeling of FLC

8.1 Simulation Results



Waveform of P_g with CPC IPC and FLC at high wind speeds



Waveform of P_g with CPC IPC and FLC at low wind speeds

From above waveforms we can clearly see that power generated wave without IPC for high and low speeds has greater fluctuations when compared to waveform using IPC and FLC controllers. Thus there is significant flicker mitigation by using Individual pitch controller and fuzzy logic controller.

9. CONCLUSIONS

The proposed model describes a method of flicker mitigation by IPC of variable-speed wind turbines with MW-level DFIG. The modeling of the wind turbine system is carried out using MATLAB Simulink. On the basis of the presented model, flicker emission is analyzed and investigated in different mean wind speeds. To reduce the flicker emission, a novel control scheme by IPC is proposed. The generator active power oscillation which leads to flicker emission is damped prominently by the IPC in both high and low wind speeds. The IPC method for flicker mitigation proposed in this thesis may be equally applicable to other types of variable speed wind turbines, such as a permanent magnet synchronous generator or a doubly salient permanent magnet generator,

Despite of shadow effects yaw errors mechanical fatigue IPC control scheme reduces the active power oscillations. So when grid connected wind turbines are controlled by this mechanism stability of grid voltage can be maintained in spite of variable speed of wind. Maximum power can be extracted at extremely low speeds and turbine speed can be controlled during high speeds. Also proposed fuzzy controller with additional wind speed as an input signal has faster response in large turbines the advantage of the controller is that the output power remains at acceptable level during regulation by the controller. It can be concluded from the simulation results that damping the generator active power oscillation by IPC along with FLC is an effective means for flicker mitigation of variable speed wind turbines during continuous operation.

10 FUTURE SCOPE

There are also drawbacks of the proposed IPC method, such as loss of a small amount of wind energy in low wind speed and high demand of the PAS. There is an alternative flicker mitigation method, which is the turbine rotor speed control taking advantage of the large rotor inertia. In this way, the wind power fluctuations can be stored in the wind turbine rotor, leading to the flicker mitigation. However, this paper is focused on the IPC method.

11 NOMENCLATURE

C_L	Lift coefficient
C_D	Drag coefficient
M	Moment of turbine
λ	Tip speed ratio
ω	rotor speed (in radians per second)
D	length of a blade
α	wind speed (m/s)
C_P	Active power cofficient
C_{PMax}	Maximum Active power cofficient
J_ω	Moment of inertia of wind turbine
J_g	Moment of inertia of generator,
T_ω,	wind turbine torque
T_e	Generator electromagnetic torque,
θ_ω	Mechanical angle of wind turbine
θ_g	Mechanical angle generator,
K	gain constant of turbine,
D	Drive train torsion damper.
V_{ds}	Voltage of stator along d-axis
V_{qs}	Voltage of stator along q-axis
R_s	Resistance of stator
R_r	Resistance of rotor
I_{ds}	Current on stator d-axis
I_{qs}	Current on stator q-axis
ω_s	Stator frequency
ω_r	Rotor frequency
ϕ_{qr}	Flux of rotor on q axis
ϕ_{qs}	Flux of stator on q axis
L_s	Stator inductance
L_r	Rotor inductor
L_{ss}	Self inductance
L_m	Mutual inductance
P_s	Stator active power
Q_s	Stator reactive power
ψ_{ds}	Flux linkage of stator d axis
ψ_{qs}	Flux linkage of stator q axis
ψ_{dr}	Flux linkage of rotor d axis
ψ_{qr}	Flux linkage of rotor q axis
ω_c	center frequency
T_{pas}	time constant of PAS
K_s	Gain of signal processor
Q	quality factor of SP
N	gear ratio
3p	third harmonics
B	collective pitch angle
P_{g3p}	active power with third harmonics
T_{sp}	time constant of SP
δ	angular contribution
ω_{3p}	center frequency of BPF
6p	sixth harmonics
Pg	

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