ISSN: 2319-8753

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 6, June 2014

Fuzzy Logic Controller for Doubly Fed Induction Generator Based Wind Energy Conversion System

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ABSTRACT: The aim of this paper is to propose a control method for a doubly-fed induction generator used in wind energy conversion systems. The proposed control algorithm is applied to a doubly fed induction generator (DFIG) whose stator is directly connected to the grid and the rotor is connected to the grid through a back-to-back AC-DC-AC PWM converters. The control of the rotor-side converter is realized by stator flux oriented control and the fuzzy controller performs robust speed control. The grid side converter (GSC) is controlled in such a way to guarantee a smooth DC voltage and ensure sinusoidal current in the grid side. The results obtained from a system using the proposed fuzzy controller show more accurate control performance and faster dynamic response with almost no steady state error when compared to a system using conventional PI controller.

KEYWORDS*:* Doubly Fed Induction Generator (DFIG), Fuzzy Logic Controller, Field Oriented Controller, Power Converters.

I. INTRODUCTION

Wind energy can meet the growing energy needs of mankind due to its clean and inexhaustible nature. Wind power generation has developed fast because of commercial application and large-scale development future. In recent years, wind power generation connected to grid has become the mainstream, which gets the support of large grid. The VSCF DFIG wind power generation has many advantages such as variable speed generation, four -quadrant power flow control, good power quality and small converter capacity so that it has become the most widely used wind generator at MW rated. In AC-excited wind generation system, the stator is directly connected to grid. The rotor is indirectly connected to grid by dual PWM converters which are able to regulate the frequency, amplitude and phase angle of rotor current based on the stator flux-oriented vector control strategy.

So far, a lot of researches concentrate on rotor current and speed controllers. Typical PI regulator is used most which can satisfy the control requirement under the normal operation conditions. However, system performance will fall down when severe disturbance happens, such as voltage dip or swell. In recent years, fuzzy control has been widely applied to power electronics system. Fuzzy control is applied to control DFIG in the paper [1]. Another PI regulator is used to control the grid side converter (GSC) by using the oriented voltage control strategy. The aim of controlling the GSC is to guarantee a smooth DC voltage and ensure sinusoidal currents in the grid side. The complete system modelling and simulation results show that system has fast dynamic response and good stability. The simulation results are highly consistent with the theoretical analysis.

The scheme of the wind energy conversion system (WECS) is presented in Fig.1.

ISSN: 2319-8753

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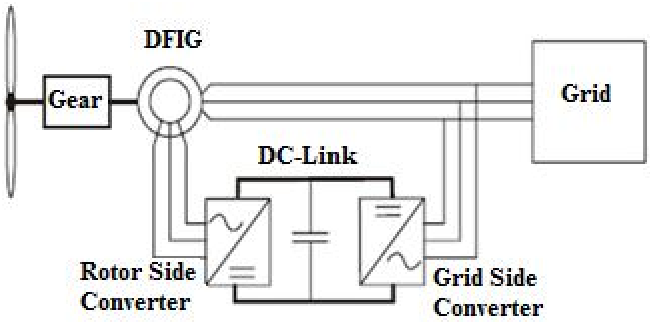

Fig.1 Scheme of the Wind System

II. WIND TURBINE MODEL AND FIELD ORIENTED CONTROL OF DFIG

A. Turbine Model

Wind turbines convert the kinetic energy present in the wind into mechanical energy by means of producing torque. The power coefficient, Cp gives the fraction of the kinetic energy that is converted into mechanical energy by the wind turbine. It is a function of the tip speed ratio (λ) and also depends on the blade pitch angle (θ) for pitch controlled turbines. The mechanical power captured by the turbine from the wind is given by the following expression [2].

$$P_t = \frac{1}{2}\rho c_p(\lambda,\beta) s\, v^3 \tag{1}$$

The Power co-efficient Cp (λ, θ) is,

$$Cp\ (\lambda, \theta) = 0.22\left(\left(\frac{116}{\lambda_i}\right) - 0.4*\theta-5\right)e^{\frac{-(12.5)}{\lambda_i}} \tag{2}$$

There is a value of optimum tip speed ratio at which the power coefficient is maximized. The variable speed turbines can be made to capture this maximum power by operating them at a blade speed corresponding to optimum tip speed ratio. This may be done by changing the shaft speed of the turbine in proportion to the change in wind speed.

B. Modelling of the DFIG

The most significant feature of wound-rotor machine which is widely used for wind power generation, is that it has to be fed from both stator and rotor side. Normally, the stator is directly connected to the grid and the rotor is interfaced through a variable frequency back to back AC-DC- AC power converter to provide bidirectional rotor power flow [3].
The operating principle of a DFIM can be analyzed using the classic theory of rotating fields and the well known d-q model, as well as both three-to-two and two-to three axes transformations. In order to deal with the machine dynamic behaviour in the most realistic possible way, both stator and rotor variables are referred to their corresponding natural reference frames in the developed model. In other words, the stator side current and voltage components are referred to a stationary reference frame, while the rotor side current and voltage components are referred to a reference frame rotating at rotor electrical speed [6].
The DFIG voltage and flux equations, expressed in Park reference frame, are given by:

$$u_{ds} = R_s i_{ds} + \frac{d\Psi_{ds}}{dt} - \omega_s \Psi_{qs} \tag{3}$$

$$u_{qs} = R_s i_{qs} + \frac{d\Psi_{qs}}{dt} + \omega_s \Psi_{ds} \tag{4}$$

$$u_{dr} = R_r i_{dr} + \frac{d\Psi_{dr}}{dt} - \omega_r \Psi_{qr} \tag{5}$$

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$$u_{qr} = R_r i_{qr} + \frac{d\Psi_{qr}}{dt} - \omega_r \Psi_{dr} \quad (6)$$

Where,

$$\begin{aligned} \Psi_{ds} &= L_s i_{ds} + M i_{dr} \\ \Psi_{qs} &= L_s i_{qs} + M i_{qr} \\ \Psi_{dr} &= L_r i_{dr} + M i_{ds} \\ \Psi_{qr} &= L_r i_{qr} + M i_{qs} \end{aligned} \quad (7)$$

The electromagnetic torque is expressed by:

$$C_{em} = \frac{3}{2} p \frac{M}{L_s} (i_{qr} \Psi_{ds} - i_{dr} \Psi_{qs}) \quad (8)$$

The mechanical equation is expressed as follow:

$$C_{em} = J \frac{d\Omega_g}{d_t} + f\Omega_g + C_r$$
(9)

Where J is the inertia, Ω_g is the generator speed, f is the mechanical damping coefficient and p is the number of pole pairs. R_s, R_r are the stator and rotor phase resistances respectively. ω_s, ω_r are respectively the synchronous angular speed of the generator and the angular speed of the rotor [4]. L_s, L_r, are respectively the stator and rotor inductances and M is the magnetizing inductance.

C. Rotor Side Converter Control

The stator flux is set aligned with the d axis and we suppose that the grid is assumed to be strong and stable so Ψ_s is constant. Moreover, the stator resistance of the DFIG is neglected [5].
Since the stator flux is aligned with the d axis, we can write $\Psi_{ds}=\Psi_s$ and $\Psi_{qs}=0$. Hence, equations (3) to (8) become respectively:

$$u_{ds} \approx 0 \quad (10)$$

$$u_s = u_{qs} \approx \omega_s \Psi_s \quad (11)$$

$$\Psi_s = L_s i_{ds} + M i_{dr} \quad (12)$$

$$0 = L_s i_{qs} + M i_{qr} \quad (13)$$

$$C_{em} = \frac{3}{2} p \frac{M}{L_s} (\Psi_s i_{qr}) \quad (14)$$

Where u_s is the stator voltage magnitude assumed to be constant.

From (14), one can establish that the electromagnetic torque can be controlled directly by acting on i_{qr} current. Then, the current reference is given by:

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$$i_{qrref} = \left(\frac{2L_s\omega_s C_{emref}}{3pMu_s}\right) \tag{15}$$

The stator reactive power is expressed by the following equation:

$$Q_s = \frac{3}{2}(u_{qs}i_{ds} - u_{ds}i_{qs}) \tag{16}$$

The equations (3.0), (3.2) are used to rewrite the stator reactive power as follow:

$$Q_s = \frac{3}{2}\frac{u_s}{L_s\omega_s}(u_s - M\omega_s i_{dr}) \tag{17}$$

From this latter equation, one can note that the stator reactive power can be controlled by acting oni_{dr}. To guarantee unitary factor power at the stator side, the reactive power command must be chosen as Q_{sref}=0. So, the direct rotor reference current is expressed as:

$$i_{drref} = \frac{u_s}{M\omega_s} \tag{18}$$

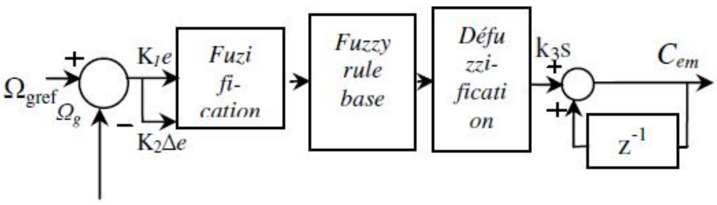

Fig.2 Fuzzy Logic Controller

The fuzzy controller (FLC) is mainly used in nonlinear systems which can't be accurately modelled and have more inputs, uncertain factors and inaccurate properties. In our case the fuzzy controller includes four parts: fuzzification, fuzzy rule base, reasoning and defuzzification as shown in the Fig. 2.
The inputs of the fuzzy controller are the error e and the variation of the error Δ_e [6].

$$e = \Omega_{gref} - \Omega_g \tag{19}$$

$$\Delta_e = (1 - z^{-1})e \tag{20}$$

The output is the increment of the electromagnetic torque.

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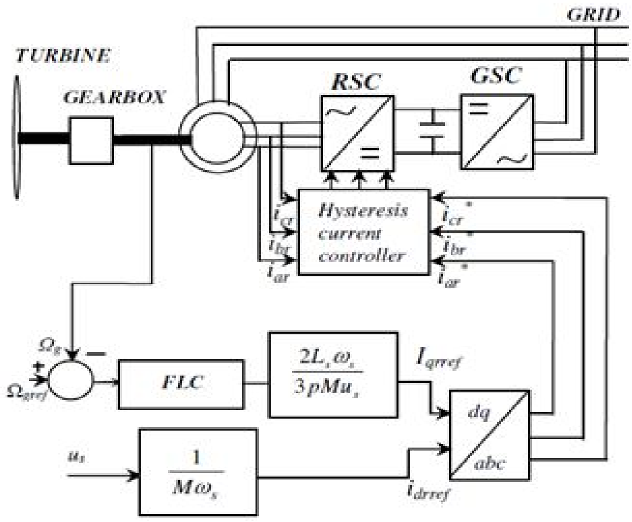

Fig.3 Block Diagram of the Rotor Side Converter Control

To obtain the output of the FLC, the de-fuzzication used in this work is based on the center of gravity method. k_1, k_2 and $k_3$are the normalization constants.

For the RSC, a reference $i_{qrref}$was derived from the speed error e and the variation of the speed error $\Delta_e$by tuning a fuzzy logic controller (FLC), as shown in Fig. 3.

Also, to guarantee a unitary factor power at the stator side, the stator reactive power command must be chosen as $Q_{sref} = 0$, so an appropriate reference current $i_{drref}$was derived. Then, both d-q reference currents were transformed to their natural abc reference frame and used for implementing the hysteresis modulation [7].

D. Rotor Side Converter Control

The grid side converter is controlled by a PI controller in such a way to guarantee a smooth DC voltage and ensure sinusoidal current in the grid side [13]. The block diagram of this converter is presented in Fig. 4.

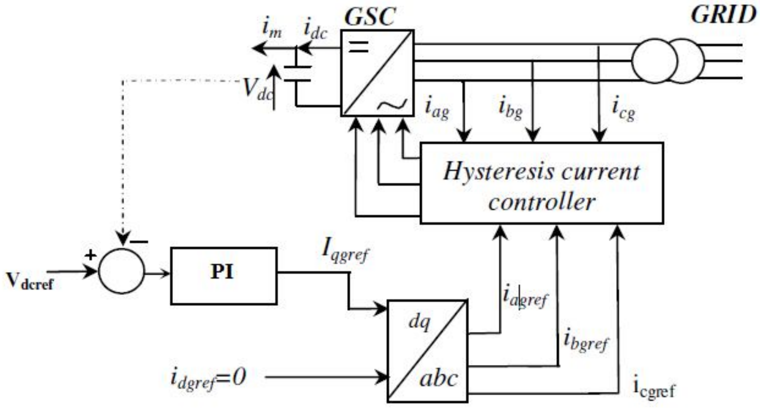

Fig.4 Block Diagram of the Grid Side Converter Control

The error is given by:

$$e_c = V_{dcref} - V_{dc} \tag{21}$$

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Also, the variation of the error is expressed by:

$$\Delta e_c = (1 - z^{-1})e_c \tag{22}$$

The grid phase voltages can be expressed as follow:

$$V_{ag} = R_g i_{ag} + L_g \frac{di_{ag}}{dt} + V_{ainv} \tag{23}$$
$$V_{bg} = R_g i_{bg} + L_g \frac{di_{bg}}{dt} + V_{binv} \tag{24}$$
$$V_{cg} = R_g i_{cg} + L_g \frac{di_{cg}}{dt} + V_{cinv} \tag{25}$$

By using park transformation, equation (23 to 24) can be expressed as follow:

$$V_{dg} = R_g i_{dg} + L_g \frac{di_{dg}}{dt} - \omega_s L_g i_{qg} + V_{dinv} \tag{26}$$

$$V_{qg} = R_g i_{qg} + L_g \frac{di_{qg}}{dt} - \omega_s L_g i_{qg} + V_{qinv} \tag{27}$$

Based on a voltage oriented control, one can write:
$V_{dg}=0$ and $V_{qg}=U_g$. Where U_g is the grid side voltage magnitude, Hence, the active and reactive powers are expressed respectively by the following equations:

$$P_g = \frac{3}{2} U_g i_{qg} \tag{28}$$
$$Q_g = \frac{3}{2} i_{dg} U_g \tag{29}$$

By neglecting the converter losses, the DC power has to be equal to the active power flowing between the grid and the grid side converter.

$$V_{dc} i_{dc} = \frac{3}{2} U_g i_{qg} \tag{30}$$
$$C \frac{dV_{dc}}{dt} = i_{dc} - i_m \tag{31}$$

The DC capacitor voltage V_{dc} is controlled by the current i_{qg} in the voltage vector-oriented reference frame [14]. Thus, a reference current i_{qgref} was derived from the dc link voltage error Δe_c and the variation of the error e_c by tuning a PI controller, as shown in Fig. 5. To guarantee a unity factor power at the grid side converter, the reactive power Q_g must be zero, so $i_{qgref} = 0$. After a dq-abc transformation of these reference currents, hysteresis modulation may then be implemented [15].

III. FUZZY LOGIC CONTROL

E. Fuzzy Controller Design

Although PI controller can play an important role in stability of the power system and especially for damping of inter-area oscillation, the best performance of the PI controller and accordingly, the performance of the DFIG depend on a suitable choice of the PI gains. Tuning the PI gains to make optimal operation is difficult task, especially, when the process is nonlinear and may change during operation. Because of the fuzzy control robustness about to many nonlinear procedures, this paper suggests the design of the fuzzy controller to control the reactive power modulation [8].
Fuzzy controller introduces a systematic method to control a nonlinear procedure based on human experience. The fuzzy controller operation is based on its capability to simulate several role implications at the same time procedure, and the output results are significantly comprehensive.

ISSN: 2319-8753

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A correctly designed fuzzy controller can provide higher operation in presence of variations in parameters, external perturbations, and load existence than conventional PI controllers. The basic formation of a fuzzy controller is consisted of four parts: fuzzifications block, fuzzy knowledge based block, a fuzzy inference engine and defuzzification block. Fig. 5 shows the block diagram of the fuzzy control for $\Delta\omega$ or $\Delta\alpha$.

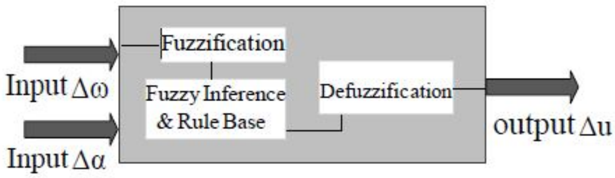


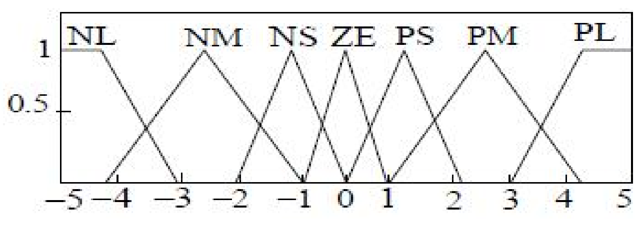
Fig.5 Block Diagram of the Fuzzy Controller

Standard triangular membership's functions were employed for the inputs and output fuzzy sets of the fuzzy controller. The schemed fuzzy sets for $\Delta\omega$ or $\Delta\alpha$ are shown in Fig.5. The control roles of the fuzzy controllers are demonstrated by set of heuristically selected fuzzy rules [9]. The schemed fuzzy rules employed in this paper for controller are stated in Table 1.

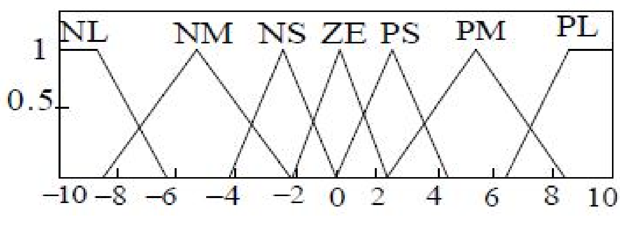
Table 1. The Fuzzy Rule Bases

Δe \ e	NB	NS	EZ	PS	PB
NB	NB	NB	NS	NS	EZ
NS	NB	NS	NS	EZ	PS
EZ	NB	NS	EZ	PS	PS
PS	NS	EZ	PS	PS	PB
PB	EZ	PS	PS	PB	PB

The fuzzy sets have been determined as: NL, negative large, NM, negative medium, NS, negative small and ZE, zero, PS, Positive small, PM positive medium, PL, positive large, respectively.



a. $\Delta\omega$ (p.u)



b. $\Delta\delta$ (p.u)

ISSN: 2319-8753

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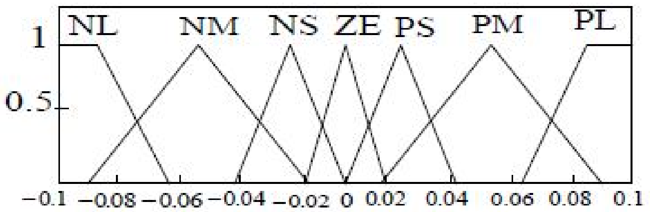

c. Δu (p.u)

Fig.6 Triangular Membership Functions for Inputs and Output Fuzzy Sets of the Fuzzy Controllers

IV. SIMULATION AND DISCUSSION

A wind power generation system (WECS) based on doubly fed induction generator (DFIG) connected to grid system with fuzzy control system is simulated using MATLAB/SIMULINK software. The frequency is set to 50Hz. The dc link voltage is regulated at 600V. The dc link capacitor is 600μF.

In Fig.7 Shows the Simulation diagram of Doubly Fed Induction Generator using the fuzzy logic controller. The proposed control algorithm is applied to a doubly fed induction generator (DFIG) whose stator is directly connected to the grid and the rotor is connected to the grid through a back-to-back AC-DC-AC PWM converters.

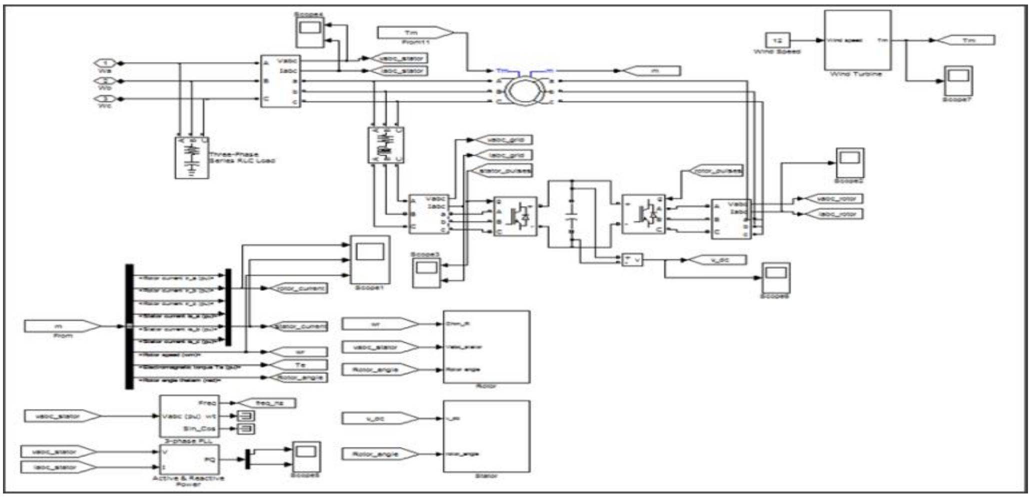

Fig.7 Simulation Diagram of Doubly Fed Induction Generator with Fuzzy Logic Controller

In Fig. 8 and 9 Shows simulation diagram of Rotor Side Converter and Grid Side Converter Controller of DFIG system with wind turbine using fuzzy logic controller. This Fuzzy Logic controller is applied to control the rotor side converter (RSC) by using a stator flux oriented strategy and an optimal speed reference which is estimated from the wind speed. The grid side converter is controlled by a PI controller in such a way to guarantee a smooth DC voltage and ensure sinusoidal current in the grid side.

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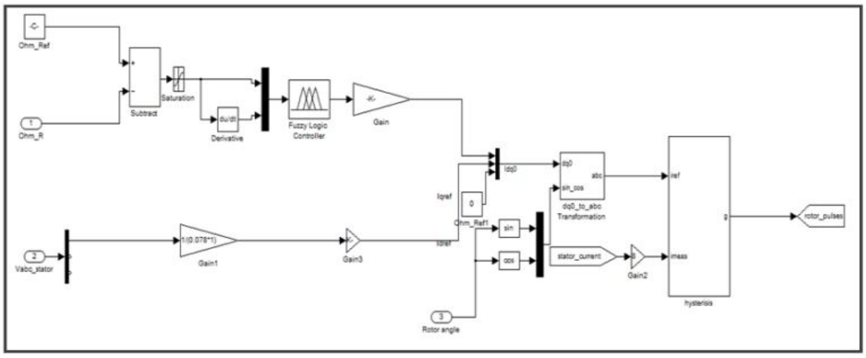

Fig.8 Rotor Side Converter Controller

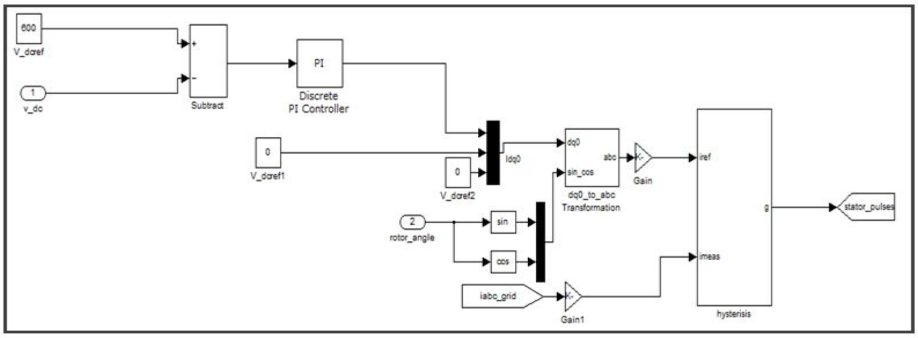

Fig.9 Grid Side Converter Controller

The simulation results of DFIG rotor side by using different control strategies for Rotor Current, Stator Current and speed,

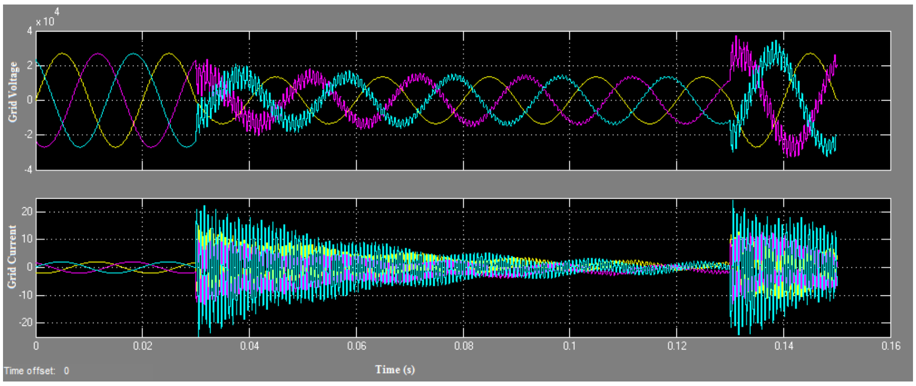

Fig.10 Grid Voltage & Current for PI Controller

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International Journal of Innovative Research in Science, Engineering and Technology

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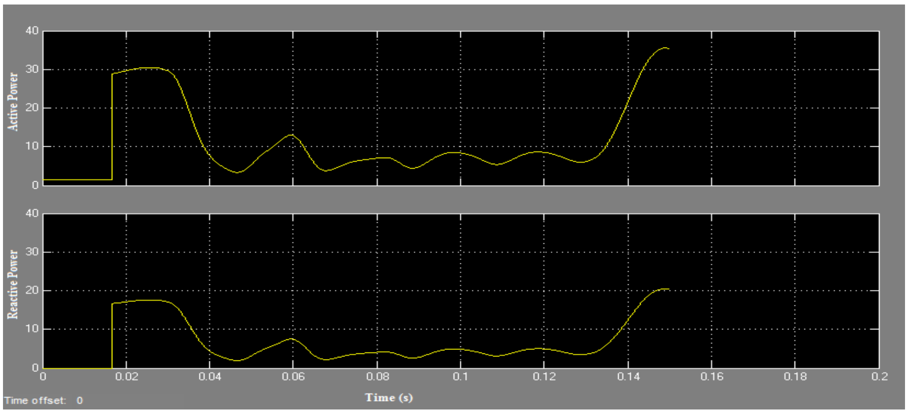

Fig.11 Active and Reactive Powers for PI Controller

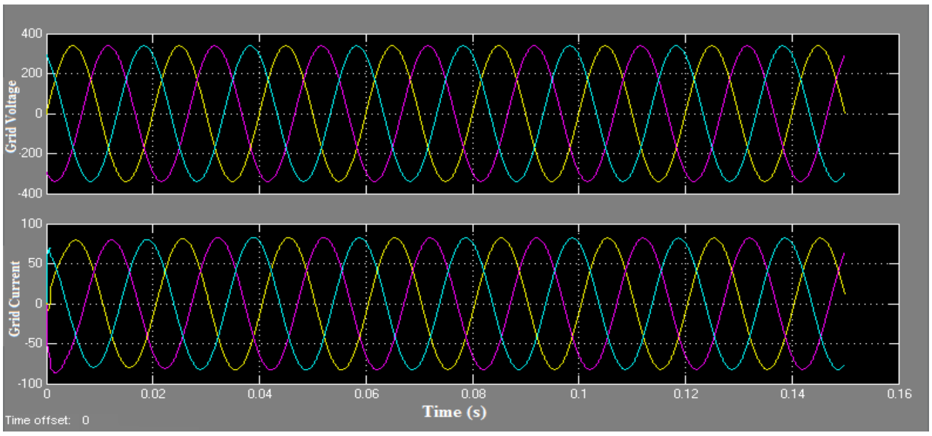

Fig.12 Grid Voltage and Current for Fuzzy Controller

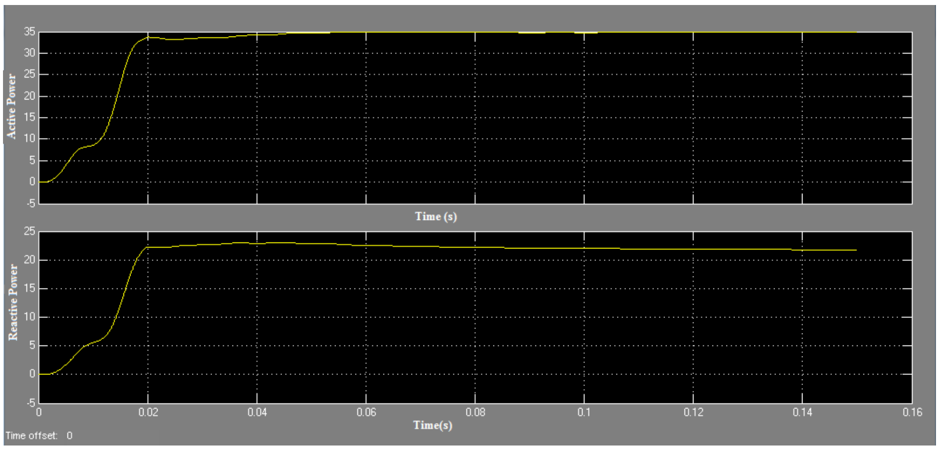

Fig.13 Active and Reactive Powers for Fuzzy Controller

Fig. 10 & 11 shows the wave forms of PI Controller not uniformed and Fig. 12 & 13 shows the fuzzy control strategy is more effective compared to PI control method for transient performance of DFIG wind power system.

ISSN: 2319-8753

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V. CONCLUSION

The fuzzy control applied to DFIG is researched, on the basis of which the simulation study is made on DFIG wind generation system. The comparative study is made between PI controller and fuzzy controller in DFIG wind power generation system. The design parameters of PI controller remain to be tested and adjusted in practical, while fuzzy controller has strong robustness to control system whose parameters varied. The results show that fuzzy controller has better performance than PI controller. The simulation results are highly consistent with theoretical analysis and verify correctness of the proposed simulation system.

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