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Power Regulation of a Wind Turbine Using Adaptive Fuzzy- PID Pitch Angle Controller

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***Abstract*—This paper considers power generation control in variable pitch wind turbines, using an adaptive fuzzy-PID controller. The pitch angle control system was simulated using MATLAB/ SIMULINK tool to test the control strategy and performance evaluation of the system. To test the controller's performance, a wind profile has been simulated and results are validated to show that the proposed controllers are effective for power regulation. To highlight the improvements of the method the proposed controller are compared to the conventional PID controller.**

***Index Terms*—Adaptive control, Fuzzy controller, PID-controller, Pitch control, Wind turbine.**

I.INTRODUCTION

In Today's world, the appetite of energy is keep on rising at a very high rate & this will only grow large and large in the coming futures as the energy needs of the emerging economies like India, China and Brazil are putting more pressure on the already high demand from the developed countries. The fact, that the reserves of the fossil fuels are limited and their prices will keep on rising; can negatively affect the growth of these economies. Moreover the economic and geopolitical risks associated with the import of fossil fuels have moved the need of Non-conventional energy resources to the top of the political agenda.

Mean while the negative effects of the climate change and pollution are becoming more apparent. These drastic changes in the climate are also affecting the water cycle, which puts dramatic consequences for electricity production patterns. Therefore the global energy challenge of our time is to tackle with the problem like: threat to climate change, safeguard security of energy supplies.

The main objective of this research work is to develop and analyze a dynamic model of Pitch angle controller for a doubly-fed induction generator (DFIG) based wind energy conversion system (WECS) using fuzzy logic operations.

Further the objective is to study the steady state performance of a controller structure that is valid for the entire wind speeds region to extract the maximum optimum power from the wind Moreover to assess the integration of this pitch controller with a typical WECS and establish a comparative study between the conventional PID controller and the fuzzy- PID controller.

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II.WIND TURBINE MODELLING

A. *Wind Turbine Power Extraction*

A wind turbine extracts energy from the wind stream by converting the kinetic energy of wind into the rotational motion required to operate an electrical generator. By virtue of the kinetic energy, the velocity of the flowing wind stream decreases. It is a general assumption that the mass of air which passes through the rotor is only affected while the mass of air which does not passes through the rotor remains unaffected.

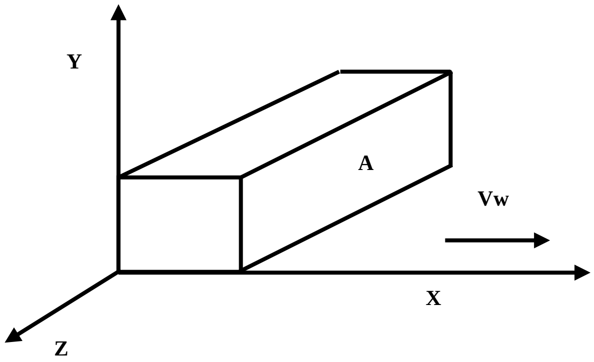

Figure 1. Packet of air moving at speed (V_w) m/s

The kinetic energy in a parcel of air of mass, m, flowing at speed, Vw in the x direction is given by (1).

$$U = \frac{1}{2}(\rho A x) V_w^2 \tag{1}$$

where, U is the kinetic energy in joules, A is the cross-sectional area in m^2, ρ is the air density in kg/m^3, and x is the thickness of the parcel in m.

The power in the wind, Pw, is the time derivative of the kinetic energy, i.e.

$$P_w = \frac{1}{2}\rho A v_w^3 \tag{2}$$

In Ideal case the mechanical power extracted from wind is the difference between the input and output power in the wind and is given by (3).

$$P_{m(ideal)} = \frac{1}{2}\rho A V_w^3 C_p \tag{3}$$

A wind turbine can only extract part of the power from the wind, which is limited by the Betz limit (maximum-59.3%) [7]. This fraction is described by the power coefficient of the turbine, Cp, which is a function of the blade pitch angle (*β*) and the tip speed ratio (*λ*) [1].

$$C_p(\lambda,\beta) = 0.52\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-21/\lambda_i} + 0.0068\lambda \tag{4}$$

$$\text{Tip Speed Ratio } (\lambda) = \frac{\omega R}{V_w} \tag{5}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{6}$$

Where, ω is the turbine speed in m/sec. and R is the radius of wind turbine blade.

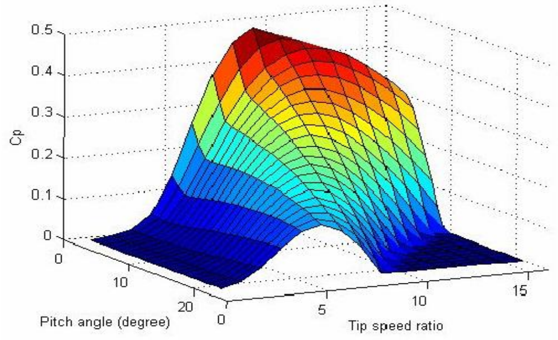

Figure 2. Surface diagram for power coefficient C_p.

Figure 2, shows a group of typical C_p-λ curves where optimum values of tip speed ratio, λ_{opt}, correspond to the maximum power coefficient, C_{p_max}. Any change in the wind speed or the rotor speed will reflect a change in the tip speed ratio leading to power factor variation. In this way the generated power will be affected. Fig. 3 shows that the mechanical power converted from the turbine blade is a function of the rotational speed, and the converted power is maximized at the particular rotational speed for various wind speeds.

The operating region of a variable-speed variable-pitch wind turbine can be illustrated by their power curve, which gives the estimated power output as a function of wind speed see Fig. 4. Three distinct wind speed points can be noticed in this power curve:

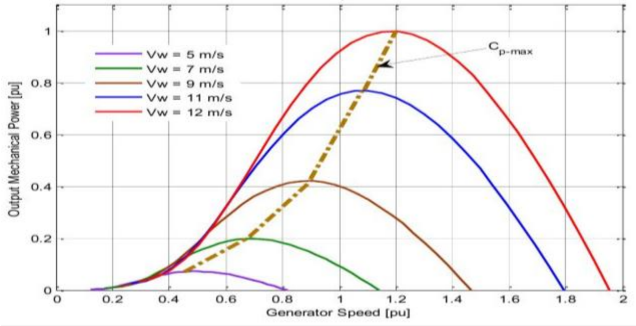

Figure 3. Mechanical power versus rotor speed characteristics.

- *Cut-in wind speed:* The lowest wind speed at which wind turbine starts to generate power.
- *Rated wind speed:* Wind speed at which the wind turbine generates the rated power, which is usually the maximum power wind turbine can produce.
- *Cut-out wind speed:* Wind speed at which the turbine ceases power generation and is shut down (with automatic brakes and/or blade pitching) to protect the turbine from mechanical damage [2].

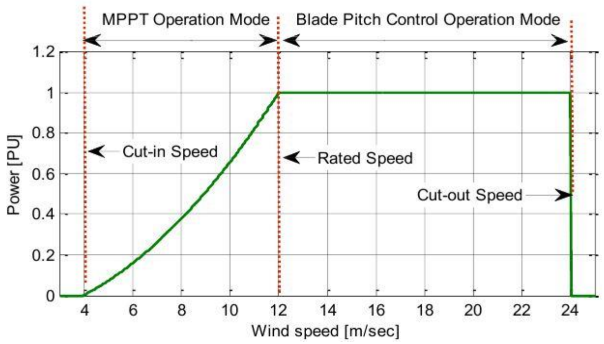

Figure 4. Power curve of a variable speed wind turbine [3].

B. *Wind Turbine Mode of Operation*

There are three distinct modes of operation for a variable speed pitch controlled wind turbines [3]. Selection of a mode of operation depends upon the available wind speeds and the amount of power output needed from the wind energy conversion system. As shown in Fig. 4, three operating modes are:

- *Maximum Power Point Tracking:* mode is used to extract maximum power from the wind, at low wind speeds to rated wind speeds by following the maximum value of power coefficient (C_{p_max}= 0.48) as shown in Fig. 3. The mechanical power extracted in this mode is given by (7).

  $$P_m = \frac{1}{2}\rho A C_{p\_max} V_w^3 \qquad (7)$$

  Figure 2, shows that power coefficient attain its maximum value of $C_{p\_max}=0.48$, when pitch angle $\beta=0°$ and tip speed ratio, $\lambda_{opt}=8.1$.
- *Blade Pitch control:* mode is operated for the wind speeds beyond the rated values, in this situation the electromagnetic torque is not enough to control the rotor speed in this way generator tends to overload region. To avoid this, the extracted power from the wind turbine must be limited and this can be done by reducing the power coefficient (C_p) of the wind turbine. As given in (4), the power coefficient can be manipulated by varying the blade pitch angle (β). Changing the blade pitch angle means slightly rotating the turbine blades along its axis [8].

As the wind speed varies, turbine speed is kept at rated speed (ω_{rated}). To maintain the output power at rated value (P_r), Corresponding value of TSR and C_p are calculated using (8).

$$\left.\begin{aligned} \lambda &= \frac{\omega_{rated} R}{V_w} \\ C_p &= \frac{P_r}{0.5 A \rho V_w} \end{aligned}\right\} \qquad (8)$$

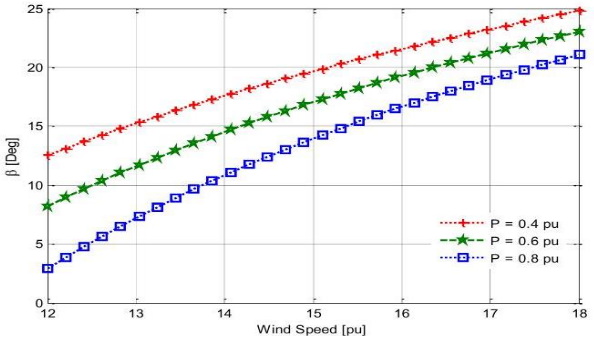

Figure 5. Power regulation operation with above rated wind speed.

- *Power Regulation*: with more and more inclusion of wind power in a power system, it is not possible to operate wind turbine in MPPT and constant power modes only. To maintain the regulated voltage and frequency, the generated power must be equal to the power demand. When the load decreases, the power output from turbine should be reduced to match the load. When the wind speed is less than the rated speed, the pitch angle (β) is always kept at zero and the λ is varied and corresponding C_p is calculated to obtain demanded power output from the wind turbine.

Then, the wind speed is calculated based upon the demanded power output (P) given by (9).

$$\left.\begin{aligned} V_w &= \left(\frac{\mathrm{P}}{0.5\mathrm{A}\rho \mathrm{C_p}}\right)^{1/3} \\ \omega_r &= \frac{\lambda \mathrm{V_w}}{\mathrm{R}} * \text{Gear Ratio} \end{aligned}\right\} \quad (9)$$

Figure 5, shows the rotor speed vs. wind speed operating points for various demanded output power (P). If the wind speed is more than the rated speed, then the turbine speed is maintained at rated speed (ωrated) and wind speed is varied. The corresponding λ is calculated and pitch angle is obtained for various values of demanded power (P), which gives corresponding Cp by (8).

III.POWER REGULATING CONTROLLERS

A. PID Controller Design

Three-term or PID (Proportional, Integral and Differential) controllers are probably the most widely used industrial controllers because of its simple structure and strong robustness. Even complex control systems may comprise a control network whose main control block is a PID module. (see Fig. 6).

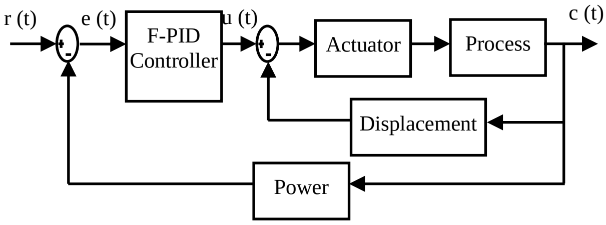

Figure 6. Closed loop pitch control system.

A PID controller is a linear controller which generates a control action u(t) depending upon the control error-e(t):

$$e(t) = r(t) - c(t) \quad (10)$$

Then the PID control action is a linear combination of proportional, integral and derivative of the error signal as given in (11).

$$u(t) = K_p e(t) + K_i \int_0^T e(t)dt + K_d \frac{de(t)}{dt} \quad (11)$$

By changing the values of these three parameters (K_p , K_i *and* K_d), control effect can be improved.

The proportional link produces a control action which is directly proportional to the input control system error signal e(t). This link creates an immediate effect on the output. In case of system stability, increasing the proportional factor can reduce the steady state error and improve the control accuracy. Only disadvantage of proportional control is that the steady state error cannot be completely eliminated. For disproportionately large values of Kp, system exhibits large overshoots and become more oscillatory. In some severe cases system can tend to unstable region too.

The integral action on error is mainly used in the forward path to eliminate the steady state velocity error but at the same time it increases the system's order making it more susceptible to instability. Integral term is used when it is required that the controller correct for any steady offset from a constant reference signal. Integral control overcomes the shortcomings of proportional control by eliminating the steady state error without the use of excessively large controller gains [10].

Derivative control action doesn't affect the steady state error but it largely affects the transient response. It is mainly used to improve the response speed and stability of the system. The output of derivative control in PID controller depends upon the rate of change of error signal. The major disadvantage of the derivative control is that it amplifies the noise signal. The derivative action is similar to a high pass filter from the perspective of filters, so we must set an appropriate differential parameter Kd.

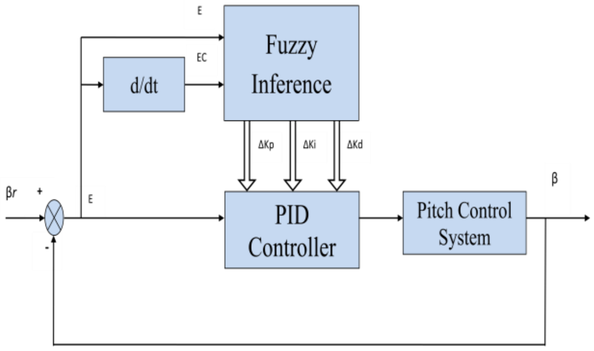

Figure 7. A two-dimensional Fuzzy controller.

B. Overview of Fuzzy logic control

Fuzzy control theory is an automatic control theory based on fuzzy set theory, To develop a control system with classical Fuzzy Logic Control (FLC) theory, following steps have been to be adopted: (i) fuzzification: the operation directed towards determining the inputs and output membership functions; (ii) setting up the rules, (iii) defuzzification: the operation directed towards converting the fuzzy result of the rules into output signal [4].

The fuzzy controller mainly consists of fuzzy module, knowledge repository module, fuzzy reasoning module and inverse fuzzy module. The principles are shown in Fig. 7.

IV.PARAMETER TUNING ALGORITHM

The traditional PID controller parameters are fixed. An adaptive Fuzzy-PID controller is made up of fuzzy controller and adaptive identification structure which based on the traditional PID controller. The initial values of PID parameters are set online through fuzzy inference. The expressions describing fuzzy logic PID parameters are given by (12):

$$\begin{aligned} Kp\,(k+1) &= Kp\,(k)\,[1 \pm \Delta Kp] \\ Ki\,(k+1) &= Ki\,(k)\,[1 \pm \Delta Ki] \\ Kd\,(k+1) &= Kd\,(k)\,[1 \pm \Delta Kd] \end{aligned} \quad (12)$$

Variable pitch wind turbines change the aerodynamic torque by the method of changing blade pitch angle, thereby to adjust the power coefficient of wind turbine, according to the difference between reference pitch angle and pitch angle of the actual output unit, through the fuzzy controller get the correction of the three parameters of pitch PID controller to achieve adaptive fuzzy control [5]. For any wind speeds beyond the rated wind speed, the FPID controller adjusts the blade pitch angle to regulate the output power.

Here we have selected the system pitch error (e) and the rate of change of deviation (ec) as the fuzzy input variables, and made the adjustment in the three parameters (ΔKp, ΔKi and ΔKd) of the output to compose it with the current PID parameters.

The variable universe of discourse for the system pitch error (*e*) and the rate of change of deviation (*ec*) is taken in the range of -1 to 1 as {-1, -0.8, -0.6, -0.4, -0.2,0,0.2,0.4,0.6,0.8,1}, then divided it into seven levels , the linguistic values of the 7 fuzzy sets were taken as {NB, NM, NS, ZO, PS, PM, PB} see Fig. 8.

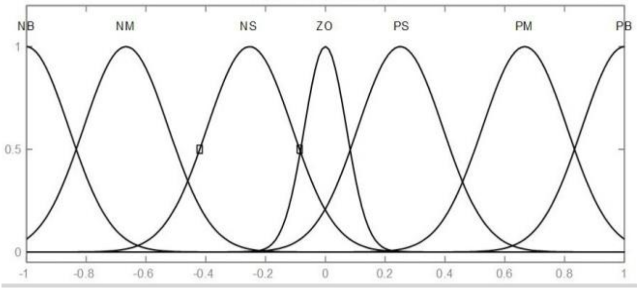

Figure 7. Membership functions for fuzzy inputs (e,ec).

Similarly the fuzzy membership functions used for output variables ΔKp, ΔKi and ΔKd is shown in Fig.9.

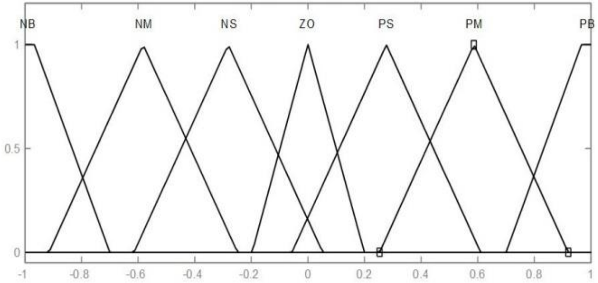

Figure 8. Memberships for fuzzy outputs (ΔKp, ΔKi andΔ Kd).

There are total 49 fuzzy rules for each ΔKp, ΔKi and ΔKd are established according to [6] as shown in Table 1-3.

TABLE 1. FUZZY RULES FOR ΔKP.

e	ec						
	NB	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
NB	PB	PB	PM	PM	PS	ZO	ZO
NM	PB	PB	PM	PS	PS	ZO	NS
NS	PM	PM	PM	PS	ZO	NS	NS
ZO	PM	PM	PS	ZO	NS	NM	NM
PS	PS	PS	ZO	NS	NS	NM	NM
PM	PS	ZO	NS	NM	NM	NM	NB
PB	ZO	ZO	NM	NM	NM	NB	NB

TABLE 2. FUZZY RULES FOR ΔKI.

e	ec						
	NB	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
NB	NB	NB	NM	NM	NS	ZO	ZO
NM	NB	NB	NM	NS	NS	ZO	ZO
NS	NB	NM	NS	NS	ZO	PS	PS
ZO	NM	NM	NS	ZO	PS	PM	PM
PS	NM	NS	ZO	PS	PS	PM	PB
PM	ZO	ZO	PS	PS	PM	PB	PB
PB	ZO	ZO	PS	PM	PM	PB	PB

TABLE 3. FUZZY RULE FOR ΔKD.

e	ec						
	NB	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
NB	PS	NS	NB	NB	NB	NM	PS
NM	PS	NS	NB	NM	NM	NS	ZO
NS	ZO	NS	NM	NS	NS	NS	ZO
ZO	ZO	NS	NS	NS	NS	NS	ZO
PS	ZO	ZO	ZO	ZO	ZO	ZO	ZO
PM	PB	NS	PS	PS	PS	PS	PB
PB	PB	PM	PM	PS	PS	PS	PB

V.SIMULATION AND RESULTS

In the Matlab/Simulink environment, Simulation of the conventional PID controller (see Fig. 10) and the Fuzzy-PID controller (see Fig. 11) is done for the regulation of output power at a rated value (P_r=1100 kW). A test simulation is performed on a DFIG-based wind energy conversion system [9] as shown in Fig. 12 with the parameters as described in Table 4.

TABLE 3. WIND TURBINE AND GEN. CHARACTERISTICS.

Base Wind Speed	9 m/sec.
Rated output Power	1100 kW
Gear Box Ratio	6
Frequency of output Power	50 Hz.
Voltage of Output Power	415 Volts

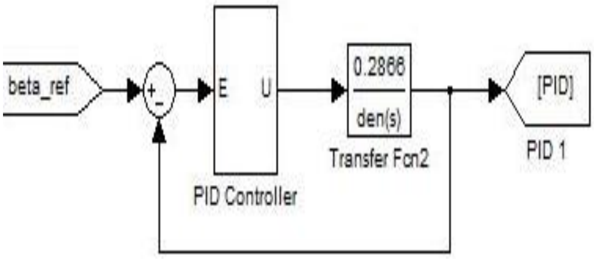

Figure 9. A conventional PID pitch controller.

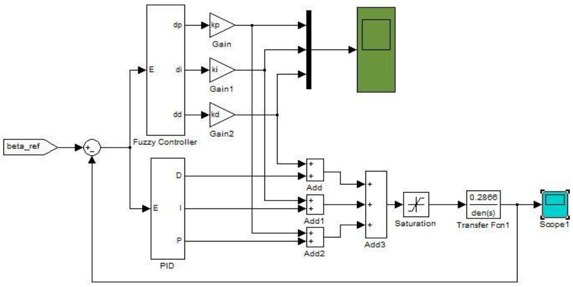

Figure 10. Fuzzy-PID Pitch controller.

Figure 13 shows the comparison between the performances of conventional PID controller and Fuzzy –PID controller for a wind profile ranging from 8 m/sec. to 12 m/sec. It is clear from Fig. 13 that the pitch control is much smoother with F-PID controller as compared to PID controller. A comparison between the output power is shown by Fig. 14.

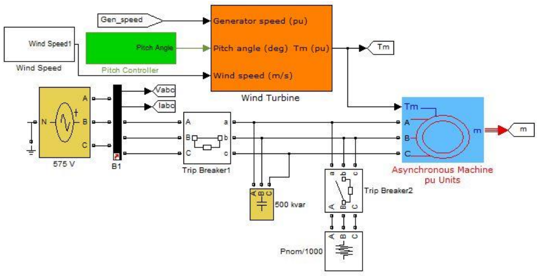

Figure 11. DFIG basedWind energy conversion system.

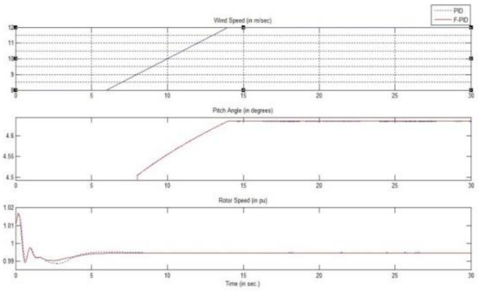

Figure 12. Wind speed, Pitch angle and Rotor speed.

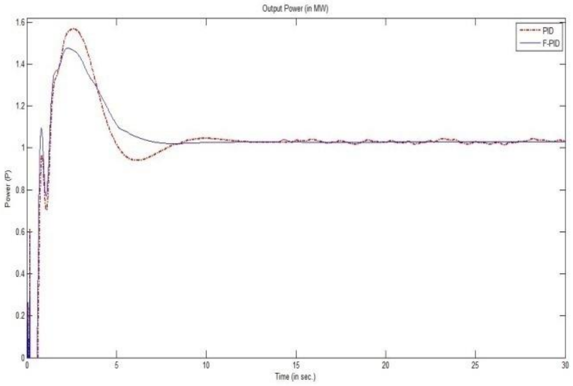

Figure 13. Output power regulation.

VI.CONCLUSION

The conventional pitch angle control strategy using different controlling variables can be implemented. However, fuzzy logic pitch angle control strategy need not well know about the wind turbine dynamics and when wind turbine contains strong non-linearities, it is more favor also. The simulation results show that the fuzzy logic controller has lowest fatigue loads and lower torque peak and lower power peak. The pitch angle of the fuzzy logic controller is less active than conventional pitch angle control with power or wind speed controlling variable, which causes less dynamic torque.

REFERENCES

1. Vladislav Akhmatov, “Variable-Speed Wind Turbines with Doubly-Fed Induction Generators--Part 1: Modelling in Dynamic Simulation Tools”. Wind Engineering, 2002,vol 26.2, pp 85-108.
2. Francoise Mei, “Small Signal Modeling and Analysis of Doubly Fed Induction Generator in Wind Power Applications,” Ph.D. dissertation, Control and Power Group Dept of Electrical and Electronic Engineering Imperial College London, University of London.
3. Bijaya Pokharel, “Modeling, Control And Analysis of a Doubly Fed Induction Generator Based Wind Turbine System With Voltage Regulation” M.S. dissertation, Deptt. of Electrical and Computer Engineering, The Faculty of Graduate school, Tennessee Technological University . Dec-2011.
4. Jajun Xi, Bin Sun and Huaqi Zhao, “Adaptive PID Controller based on Single Neuron for Permanent Magnet Synchronous Machine”, Electrical Power Automation Equipment, Vol.23, No. 10, 2003, pp. 59-61.
5. Xingjia Yao, Z. Zhang and C. Zhang, ‘‘The Study of Adaptive Independence Electrical Drive Blade Pitch Control Technology”, Proceeding of International Conference on Electrical Machines and Systems, 2007, pp. 828-833.
6. Linjing Hu, Dongmin Xi and Tao Liu, “Research of Wind Generation Pitch System Bases on Fuzzy Adaptive PID”, 2nd International conference on intelligent control and Information Processing, 2011, pp. 97-100.
7. Danish Wind Industry Association. Know How: Guided tour [online]. Available: http://www.windpower.org.
8. Wind Energy Background [Online]. Available: http://www.dolcera.com.
9. Asynchronous Generators [Online]. Available: http://www.windturbines.net.
10. Jainguang Qi and Yongxin Liu, ”PID Control in Adjustable-pitch Wind Turbine System Based on Fuzzy Control.” Proceedings of 2nd International conference on Industrial Mechatronics and Automation, 2010, pp 341-344.

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