Different Strategies in Designing Pitch Controller for Variable Speed Wind Turbine

Ebrahim Tarsayi
Master of Science Student
And Electronic Engineering
Khorasan Institute of Higher Education
Mashhad, Iran
etarsayi@yahoo.com

Ali Karsaz
Assistant Professor
Dept. of Electrical Engineering,
Khorasan Institute of Higher Education
Mashhad, Iran
karsaz@khorasan.ac.ir

***Abstract*— In this paper the detailed model of a typical wind turbine with permanent magnet synchronous generator is extracted by using mathematical equations, simulation and system identification. There are a lot of limitations in this turbine performance and control caused by mismatching among components which is not avoidable during the production process. The main idea of pitch controller is to consolidation the power and generator speed over the rated wind speeds. An efficient pitch controller will lead to reduce the mechanical stress and fatigue on the pitch actuator and guarantee the wind turbine stability. In this paper four pitch control methods are presented to pitch regulation and performance enhancement of a 108 KW wind turbine. These controllers are utilized and compared to regulation of the pitch angle in practical application. These four controllers are PI, fuzzy, fuzzy-PI and gain scheduled PI controllers which are designed to be applied to an actual wind turbine. The result of comparison among these four methods shows that the fuzzy-PI controller provides an appropriate pitch control signal.**

Keywords—Fuzzy Logic; Gain Scheduling; PI Controller; Pitch Control Wind Turbine.

I. INTRODUCTION

A wind turbine is a device that converts mechanical energy captured from the wind into the electrical power. Nowadays the wind turbines are manufactured in a wide range of vertical and horizontal axis type [1]. Wind power, as an alternative to fossil fuels, is accessible, renewable, widely distributed, clean, produces no greenhouse gas emission during operation and uses little land. As of 2011, Denmark is generating more than a quarter of its electricity from wind and 83 countries around the world are using wind power to supply the power grid. In 2010 wind energy production was over 2.5% of total worldwide electricity usage, and growing rapidly at more than 25% per annum [2,3]. At the end of 2013, worldwide nominal capacity of wind-powered generators was 318 GW, growing by 35 GW over the preceding year [3, 4]. It is predicted that the installed wind capacity in China will be about 40 GW till 2020 [5].

There are a great number of papers and technical reports that presented a pitch controller to regulate the output power and to stabilize the generator speed of wind turbines. The General Electric (GE) report presented a PI controller based on the feedback of the generator speed to regulate the pitch angle and a pitch compensation module based on the electrical power to adjust the pitch command while a sudden change occurs in the wind speed. This method will fail when the electrical power involves flickers caused by the network harmonics [5,6]. In [7] a mathematical method is represented to calculate the gains of a PI pitch angle controller for a 5 MW wind turbine. Firstly, the power coefficient characteristics for various pitch angles are calculated. Secondly, the output powers vs. rotor speed curves from cut-in to cut-out wind speeds are simulated. Finally, the results are compared using a wind turbine model to determinate turbine's tracking characteristic. This method needs the LIDAR sensor to measure the wind speed. The controller gains will be changed for different wind speeds. The LIDAR sensor is expensive and is not affordable for low power wind turbines [8]. In [9] a new design algorithm for extracting the gains of the PI pitch controller for the wind turbines is presented. This method leads to a proportional and an integral gain fixed for all the wind speeds. In the following it is shown that a fixed gain PI controller will lead to unwanted pitch signal fluctuation specially in higher wind speeds.

These methods do not consider the mismatching problem that occurs during the production procedure. There are a lot of limitations in this turbine performance and control caused by mismatching among components. An efficient pitch controller will lead to reduce the mechanical stress and fatigue on the pitch actuator and guarantee the wind turbine stability.

In this paper four pitch control methods are presented to pitch regulation and performance enhancement of a 108 KW wind turbine. These controllers are utilized and compared to regulation of the pitch angle in practical application. These four controllers are PI, fuzzy, fuzzy-PI and gain scheduled PI controllers which are designed to be applied to an actual wind turbine. The result of comparison among these four methods shows that the fuzzy-PI controller provides an appropriate pitch control signal. In section 2 a brief introduction is presented on the wind turbine structure and components. Section 3 and 4are assigned to considering different types of controllers and test results respectively and section 5 concludes the paper.

II. WIND TURBINE STRUCTURE AND COMPONENTS

As it is shown in Fig. 1, there are four main parts in a wind turbine: the base, tower, nacelle and blades. The blades capture the mechanical power from the wind and transmit it to an electrical generator located in the nacelle [10].There are a generator and a gearbox in the nacelle. The blades are attached to the generator through a series of gears. The generators can be either variable or fixed speed. Variable speed generators produce electricity at a varying frequency, which must be corrected to 50 or 60 Hz before it is fed into the grid [10-11].

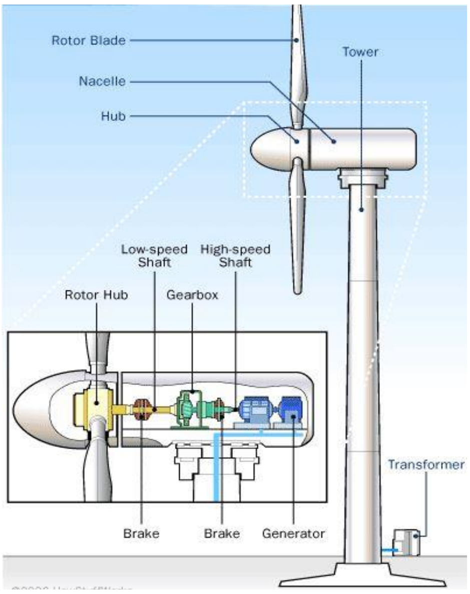

Fig. 1. The wind turbine components [11]

It is necessary to model, identify and simulate the subsystems of a wind turbine to produce an efficient model which is practical to control design. The wind turbine components are classified into two main categories, the mechanical and the electrical parts. These two parts are discussed in the following subsections [12].

A. *Mechanical Components (Blade, Aerodynamics & Power Transmission System)*

The MATLAB wind turbine block shown in Fig. 2, is used to model and simulate the mechanical components of the wind turbine. The inputs are generator speed, pitch angle and wind speed. The outputs include the aerodynamic torque and reference rotor speed which provide the mechanical power by multiplication. According to the MATLAB block settings the mechanical part efficiency is about 76 % and the generator speed is selected about 98.74 % of the nominal speed. The main goal of these selections is to generate a semi-actual Simulink model.

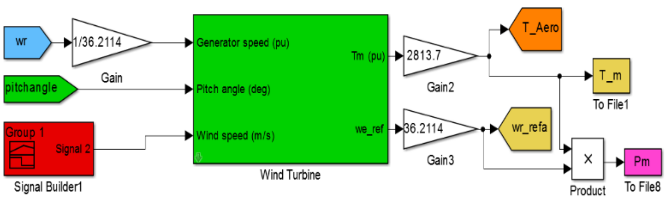

Fig. 2. Wind turbine block to model the mechanical components

B. *Electrical Components (Generator & Power Converter)*

The electrical components are summarized in generator and power converter. The permanent magnet synchronous generator (PMSG) is shown in Fig. 3. In these types of generators, the permanent magnet causes the DC excitation in the generator windings. The advantages of this type of generators in comparison with the other types are higher efficiency, controllable terminal voltage and reactive power. Besides these advantages, having no resistance losses and no need for an extra power supply to excite a generator are some of the distinction of PMSG. Another advantage of PMSG is the ability of bringing out the gearbox while increasing the generator poles. This advantage decreases the mechanical losses and costs [12-13].

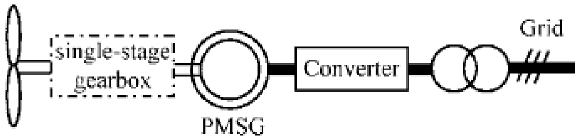

Fig. 3. PSMG and single stage gearbox

The generator is modeled by using the PMSG block in MATLAB Simulink. The input of this block which is shown in Fig. 4, is the aerodynamic torque and the outputs include the phase voltages and currents.

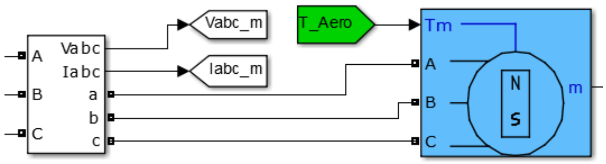

Fig. 4. PMSG block in MATLAB

The power produced by the generator is stabilized and synchronized with the grid frequency to inject to the power network by a three phase back to back converter. The converter should track and control the MPPT curve of the wind turbine. An output filter is utilized to eliminate the harmonics [14]. The general structure and the simulated control system of the converter are shown in Fig. 5 and Fig. 6, respectively. The converter controls the generator speed through the generator current adjustment by using two PI controllers. The generator speed error is entered to a PI controller to produce the generator q axis reference current. This reference current is compared with a generator actual current and the error is injected to another PI controller to adjust the current by utilizing the voltage. The d axis current is set to zero through another control loop.

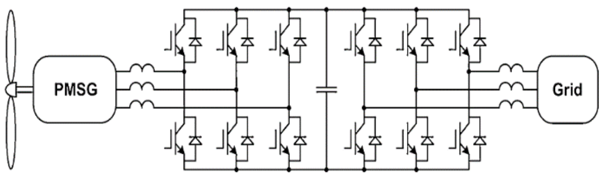

Fig. 5. A three phase back to back converter

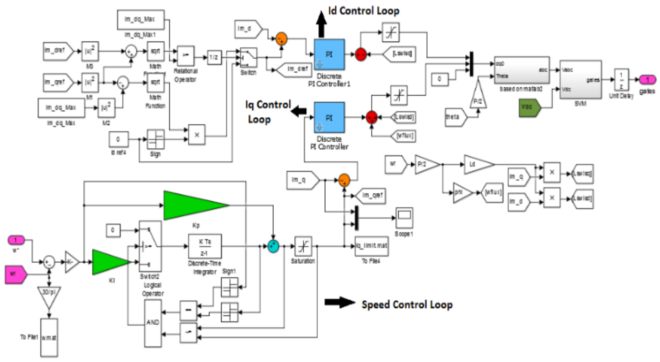

Fig. 6. Six switch back to back converter control system

The aerodynamic power produced by the blades, P_ω, can be calculated through by (1). In this equation ρ is the air density, r is the rotor radius, v presents the wind speed and β is the pitch angle. The power coefficient is calculated through (2). In this equation ω_m shows the angular rotor speed.

$$P_\omega = \frac{\rho\pi r^3 v^2 C_p(\lambda,\beta)}{2} \tag{1}$$

$$\lambda = \frac{r\omega_m}{v} \tag{2}$$

The aerodynamic torque as shown in (3) is related to P_ω and ω_m.

$$T_\omega = \frac{P_\omega}{\omega_m} = \frac{\rho\pi r^3 v^2 C_p(\lambda,\beta)}{2\lambda} \tag{3}$$

The drive model is shown in (4). In this equation ω_e ($\omega_e = P\omega_g = PN\omega_m$) is the electrical rotor speed and ω_g is the mechanical rotor speed. The number of the poles is shown by P, turbine inertia is shown by J, N is showing the gearbox Conversion ratio and T_e is showing the electrical torque [15].

$$\dot{\omega}_e = \frac{P}{J}\left(\frac{T_\omega}{N} + T_e\right) \tag{4}$$

Fig. 7 shows the power coefficient characteristics of a typical wind turbine which is different at various pitch angles. The maximum power point tracking (MPPT) will be extracted through the power coefficient characteristics. The MPPT curve used in the simulations is shown in Fig. 8. In the simulated wind turbine, MPPT is realized by the using a piecewise linear look up table. Maximum power point tracking (MPPT) is a technique that wind turbines, solar battery chargers and similar devices use to obtain the maximum possible power from the power source. In the simulated wind turbine, the MPPT procedure is implemented by the convertor.

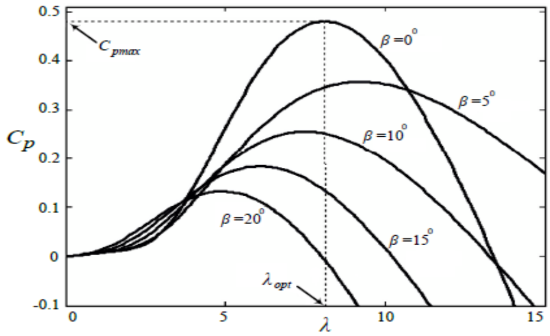

Fig. 7. Power coefficient characteristics of a typical wind turbine [14]

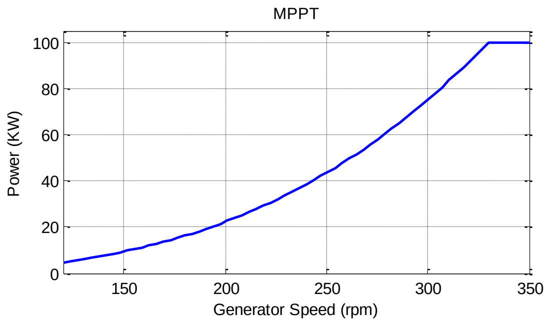

Fig. 8. MPPT curve of the simulated wind turbine

III. Controller Design

Types of controller are used to fix and level the output power and the rotor speed in different operating regions. The block diagram of these controllers is shown in Fig. 9. When the wind speed is lower than the rated, the speed controller adjusts the rotor speed so that the maximum power can be obtained from the wind. In other phrase, the speed controller adjusts the tip speed ratio (λ) at its maximum point. When the wind speed is upper than the rated, the pitch controller adjusts the rotor speed at the rated value by increasing the pitch angle of the blades. While the wind speed is lower than the rated value, the pitch angle is controlled so that the maximum power can be obtained from the wind energy [10]. Pitch control limits the output power when the wind speed is over the rated value. The PI controller is a widespread method for adjusting the pitch angle.

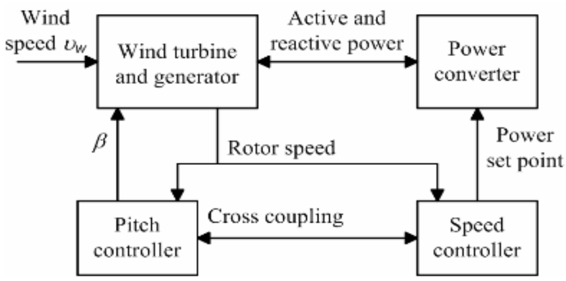

Fig. 9. Two types of controller are used in variable speed wind turbines [10]

In the following, four control methods are utilized to produce different pitch controllers for a variable speed wind turbine. These four controllers include a simple PI controller, a fuzzy controller, a gain scheduled PI controller and a fuzzy-PI controller. The aim is to achieve to an appropriate controller that is able to regulate the pitch angle, generator speed and the output power. The supposed parameters of the wind turbine are shown in Table I.

TABLE I. THE 108 KW WIND TURBINE PARAMETERS

Name	Symbol	Value
Inertia	J	1000
Air Density	ρ	1.05
Nominal Gird Power	P_{grid}	108 KW
Generator Inductance	L	0.001 H
Generator Resistance	RS	0.17 Ω
Number of Pair Poles	P	11
Nominal Generator Speed	ω_{ref}	320 rpm
Rated Wind Speed	---	9 m/s

A. *PI Tuning Using First Order Ziegler Nichols Method*

The most useful and also simplest method for pitch control is the use of the PI controllers. In Fig. 10 the pitch control system based on the generator speed error is shown. The controller output is the reference value of the pitch angle [15].The proportional and integral gains of the PI controller is extracted by using the first order Ziegler Nichols method. For the first step the generator speed is fixed on 350 rpm in wind 9 m/s. The pitch angle changed from 0.5 to 1 degree suddenly and according to the step response of the generator speed, the proportional and integral gain of the PI controller will be designed.

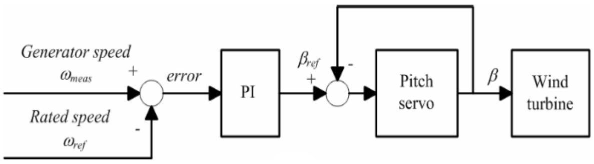

Fig. 10. Pitch angle control based on the generator speed error

According to the first order Ziegler Nichols method, at this wind speed, the gain K and the time constant τ and the delay τ_d in (5) are calculated as $K = 0.35,\ \tau = 1.4$ and $\tau_d = 0.636$.

$$G_{first\ order} = \frac{K}{\tau S + 1} e^{-\tau_d S} \quad (5)$$

Therefore the controller gain is equal to $K_P = 5.67$ and the integrator time constant is equal to $T_i = 2.1$. The transfer function of the controller is shown in (6).The block diagram realization of PI controller is shown in Fig. 11.

$$G_{Controller}(s) = K_P\left(1 + \frac{1}{\tau_i S}\right) \quad (6)$$

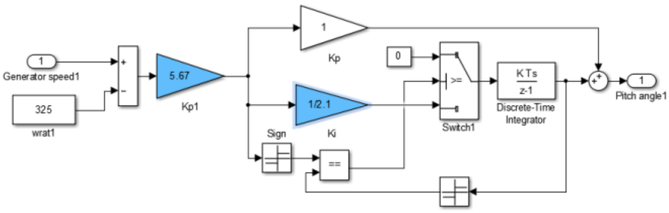

Fig. 11. The block diagram realization of PI controller

B. *The Gain Scheduled PI Controller*

The Ziegler Nichols test shown in Fig. 9 is repeated at different wind speeds and the controller gains and the integrator time constants are calculated for different wind regions. The Table II extracted from this collection of the tests, includes K_P, T_i, pitch angle to control the generator speed at 350 rpm and pitch angle to control the generator speed at 320 rpm for different wind speeds. The wind region is recognized based on the current pitch signal. In different wind region the pitch controller increases the pitch angle to stabilize the generator speed at 320 rpm. Therefore the current pitch angle specifies the wind region. Because of simplicity, T_i is supposed to be fixed in 0.6 second and the controller gain will be determined according to the current pitch angle based on the data represented by table II. In that case the controller gain will be changed in different region based on the pitch angle. The block diagram realization of gain scheduled PI controller is shown in Fig. 12 respectively.

TABLE II. THE GAIN SCHEDULING TABLE

Wind (m/s)	Pitch(320 rpm) in degree	K_P	T_i (Second)
9	0.3	5.67	2.1
10	2	3.93	2
11	7.4	3.33	1.98
12	9.2	3.2	1.98
13	11	3.18	1.95
14	12.5	3.02	1.8
15	14	2.96	1.75
16	15.5	2.93	1.73
17	16.5	2.85	1.7
18	18	2.79	1.68

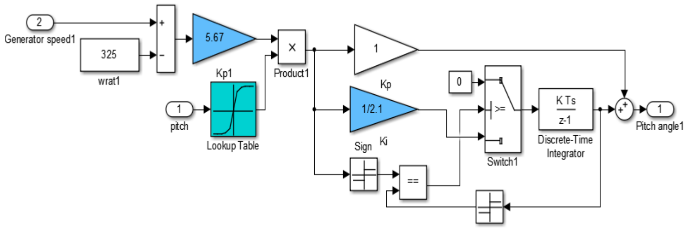

Fig. 12. The block diagram realization of gain scheduled PI controller

C. *The Fuzzy Controller*

In fuzzy systems, decision making is done based on the inputs, linguistic tags and membership degrees. The fuzzy logic is an appropriate choice to develop different kind s of controllers. It can be used as a direct controller and as a gain adapter for the PI controller. In this section the fuzzy logic is utilized as a direct controller to develop pitch signal for the simulated wind turbine. In the next section the fuzzy logic is used for the gain scheduling of the PI controller [16].

In this paper the fuzzy controller is designed based on the simple PI controller described in section 3-1 and the fine tuning procedure is done. The realization of the fuzzy control system is shown in Fig. 13.

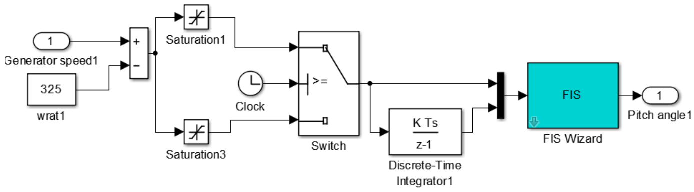

Fig. 13. The realization of the fuzzy control system

D. The Fuzzy-PI Controller

To design the fuzzy-PI controller, error and the integral error of the gain scheduled PI controller and its command signal is injected as inputs and outputs to the fuzzy inference system. The identified fuzzy system is utilized as the gain adapter block for the PI controller. The fuzzy inference system is finely tuned and then applied to the simulated wind turbine. In both fuzzy and fuzzy-PI controller the fuzzy system learning procedure is done based on the gradient descent and least square estimation (LSE) method. The premise parameters are identified by using the gradient descent method because the output is nonlinear respect to them. The consequence parameters are identified by using the LSE method because the output is linear respect to them. This identification method is called the hybrid learning procedure. The advantages of this method are reducing the identification time and avoidance of local extremum points [7-16]. The realization of the fuzzy control system is shown in Fig. 14.

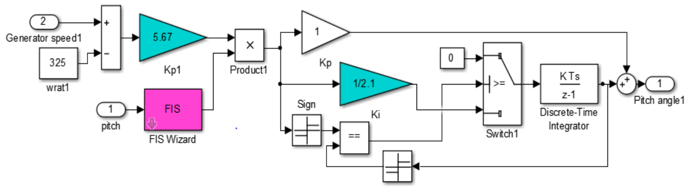

FIG. 14. THE REALIZATION OF THE FUZZY-PI CONTROL SYSTEM

IV. SIMULATION RESULTS AND COMPARISON

According to the previous sections and modeling the electrical and mechanical components, the obtained Simulink block diagram is shown in Fig. 15. The simulation tests of the four designed controllers are done on this model with the wind signal plotted in Fig. 16.

As the wind speed is the same in all simulation tests, the results are comparable. The results are shown in Fig. 17 to Fig. 19. As it is shown in Fig. 17, the fuzzy-PI controller and the gain scheduled PI controller provide a more appropriate speed control than two other controllers. Generator speed variations around the nominal speed are smoother than the two others. In Fig. 18, the output power injected to the grid is plotted for the four controllers. The wind turbine nominal mechanical power is about 108 KW and the efficiency is about 76%, therefore, the nominal grid power is about 82 KW. As it is shown in figure 18 the fuzzy-PI and gain scheduled PI controllers provide a smoother output power in comparison with two other controllers.

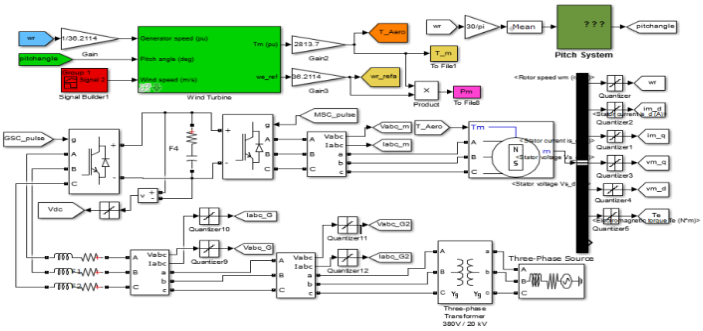

Fig. 15. Simulink block diagram of the 108 KW wind turbine

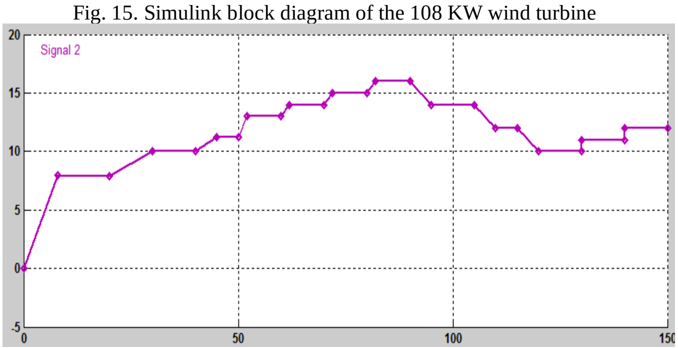

Fig. 16. Wind signal used in the simulation tests

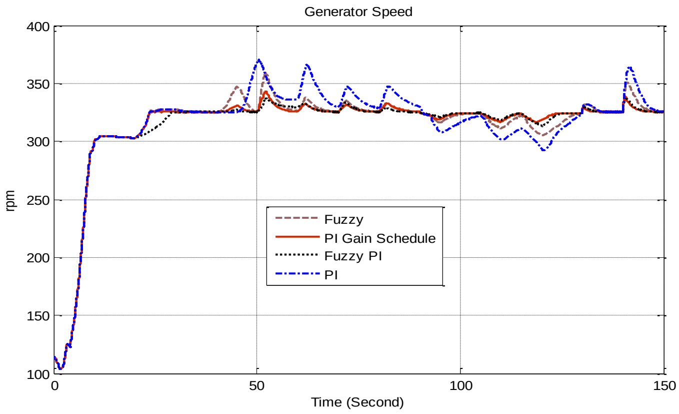

Fig. 17. Generator speed

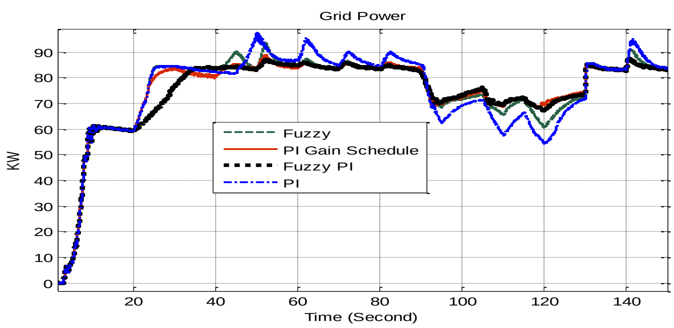

Fig. 18. Grid power

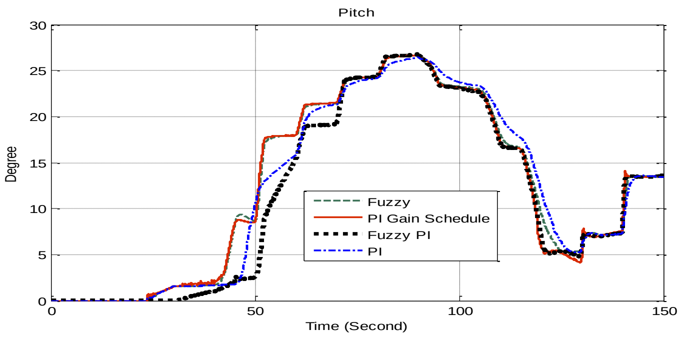

Fig. 19. Pitch signal

In Fig. 19, the pitch angle variations for the four controllers are plotted. The pitch signal for the fuzzy-PI controller is smoother in comparison with others. Table III shows the Root Mean Square Error (RMSE) of the generator speed and the grid power around the rated speed (320 rpm) and nominal power (82 KW). RMSE is an adequate numerical criterion to calculate the controllers performance. RMSE is calculated through (7).

$$RMSE = \sqrt{\sum_{i=1}^{n}(y_i - y_{nominal})^2 / n} \quad (7)$$

In this equation, $y_{nominal}$ is the nominal value and it is constant, y_i is the i^{th} sample of the variable and n is the number of samples in y vector.

TABLE III. COMPRATION RMS ERORR

	PI	Gain Scheduled PI	Fuzzy	Fuzzy-PI
Generator Speed (rpm)	16.527	4.1737	9.0175	3.9933
Grid Power (KW)	11.324	6.46	8.21	4.41

As it is shown in table 3, the RMSE criterion for fuzzy-PI controller is smaller than the other methods utilized in this paper. This table shows that the fuzzy-PI controller stabilized the generator speed and grid power in their nominal points. Therefore the fuzzy-PI controller which is using the adaptive PI gains, provides a more stable and smoother response in comparison with the others. The fuzzy inference system used in this paper, has 25 fuzzy rules.

V. CONCLUTION

In this paper the wind turbine subsystems and components are discussed and modeled in MATLAB and a complete model is obtained for the wind turbine system. As it is mentioned the pitch angle control is of great importance in wind turbine and it is necessary to design an adequate pitch controller to guarantee the stability and safety of the variable speed wind turbine. The four control strategies are introduced and applied on the wind turbine detailed model. The results are compared and analyzed to choose an appropriate controller for the wind turbine practical simulator.

REFERENCES

[1] Baogang Hu, George K. I. Mann, and Raymond G. Gosine, "New Methodology for Analytical and Optimal Design of Fuzzy PID Controllers", IEEE Transactions on Fuzzy Systems, Vol. 7, NO. 5, 1999.

[2] Lucy Y. Pao and Kathryn E. Johnson, "A Tutorial on the Dynamics and Control of Wind Turbines and Wind Farms", 2009 American Control Conf., Hyatt Regency Riverfront, St. Louis, MO, USA June 10-12, 2009.

[3] C. Buenoa, J.A. Carta,"Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands", Renewable and Sustainable Energy Reviews, 10 (2006) 312–340, Elsevier 2006.

[4] Xia Changliang, Song Zhanfeng," Wind energy in China: Current scenario and future perspectives", Renewable and Sustainable Energy Reviews , Volume 13, Issue 8, October 2009, Pages 1966–1974.

[5] Nicholas W. Miller, William W. Price, Juan J. Sanchez-Gasca, "Dynamic Modeling of GE 1.5 and 3.6 Wind Turbine-Generators", GE Power Systems Energy Consulting, October 27, 2003.

[6] Weihao Hu, Yunqian Zhang, Zhe Chen and Yanting Hu,"Flicker Mitigation by Speed Control of Permanent Magnet Synchronous Generator Variable –Speed Wind Turbines", Energies 2013-6, Open Access.

[7] Abdulhamed Hwas and Reza Katebi,"Wind Turbine Control Using PI Pitch Angle Controller", IFAC Conference on Advances in PID Control, Brescia (Italy), March 28-30, 2012.

[8] M. Harris, M. Hand, A. Wright," Lidar for Turbine Control", Technical report, NREL/TP-500-39154, January 2006.

[9] Morten H. Hansen, Anca Hansen, Torben J. Larsen, Stig Øye, Poul Sørensen and Peter Fuglsang," Control design for a pitch-regulated, variable speed wind turbine", Risø National Laboratory, Roskilde, Denmark, January 2005.

[10] Shao Zhang, Nanyang Technol, King-Jet Tseng, Vilathgamuwa, D.M., Trong Duy Nguyen, "Design of a Robust Grid Interface System for PMSG-Based Wind Turbine Generators", IEEE Transactions on Industrial Electronics, Volume:58 , Issue: 1 , Jan. 2011.

[11] Hong-Woo Kim, Sung-Soo Kim, Hee-Sang Ko,"Modeling and control of PMSG-based variable-speed wind turbine", Electric Power Systems Research, Volume 80, Issue 1, January 2010, Pages 46–52.

[12] Parisa Tavakoli, Nima Vaezi, Seyed Kamal Hosseini Sani, "Design MV-STR Pitch Controller For 100 KW Wind Turbine", The International Congress on Technology, Communication and Knowledge, ICTCK2015, Islamic Azad University of Mashhad, November 2015.

[13] Andoni Urtasun, Pablo Sanchis, Idoia San Martín, Jesús López, Luis Marroyo, "Modeling of small wind turbines based on PMSG with diode bridge forsensorless maximum power tracking", Renewable Energy, Volume 55, July 2013, Pages 138–149.

[14] Yuanye Xia,Ahmed, K.H., Williams, B.W., "Wind Turbine Power Coefficient Analysis of a New Maximum Power Point Tracking Technique ", IEEE Transactions on Industrial Electronics , Volume: 60, Issue: 3 , October 2012.

[15] K.R.M. Vijaya Chandrakala, S. Balamurugan, K. Sankaranarayanan, "Variable structure fuzzy gain scheduling based load frequency controller for multi-source multi area hydro thermal system", International Journal of Electrical Power & Energy SystemsVolume 53, December 2013, Pages 375–381.

[16] Luis Alberto Torres Salomao, Hugo Gámez Cuatzin, Juan Anzurez Marín and Isidro I. Lázaro Castillo,"Fuzzy-PI Control, PI Control and Fuzzy Logic Control Comparison Applied to a Fixed Speed Horizontal Axis 1.5 MW Wind Turbine", Proceedings of the World Congress on Engineering and Computer Science 2012 Vol II, WCECS 2012, October 24-26, 2012, San Francisco, USA.