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Hybrid Fuzzy Logic Pitch Angle Controller to A PMSG Wind Turbine System

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ABSTRACT

The Pitch angle control is the best practice to regulate the aerodynamic torque of the wind turbine at high wind speeds. The mathematical model of the wind turbine system is required for the conventional pitch angle control which usually uses Proportional Integral (PI) and Proportional-Integral-Derivative(PID) controller. In this paper a novel Hybrid Fuzzy Logic controller is designed to control Pitch angle, it doesn't require much knowledge of system model. Taking generator output power error and turbine speed as inputs the FLC produces Pitch angle reference, will compensate non-linear sensitivity of the wind turbine. The proposed method is carried out on a 2MW Permanent Magnet Synchronous generator (PMSG) wind turbine system at wind speeds of 12m/s and 14m/s in MATLAB/Simulink.

Keywords : Hybrid Fuzzy Logic controller, Pitch angle, Permanent Magnet Synchronous Generator, Wind Turbine

I. INTRODUCTION

In recent years most of the wind turbines installed are of type pitch adjusting variable wind speed. These wind turbines uses two controllers which are cross-coupled each other, shown in Fig. 1. During below rated wind speed, maximum power ouput is obtained from the wind turbine by continuously adjusting the speed of the rotor using speed controller(MPPT method).

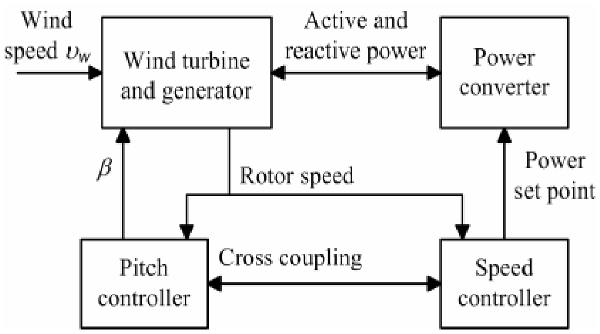


Figure 1. Block diagram of variable-speed wind turbine

AT wind speeds above rated value the rotational speed and output power of the wind turbine is kept constant using pitch angle control.

For regulating the aerodynamic power captured by the wind turbine at the high-wind speed regions, several pitch angle control methods have been suggested. The proportional–integral (PI) or proportional—integral–derivative (PID) based-pitch angle controllers have been often used for the power regulation [2], [5]–[6]. The disadvantage of this method is that the control performance is deteriorated when the operating points are changed since the controller design is based on the turbine model which is linearized at the operating points by a small signal analysis. On the other hand, the gain scheduling control is presented for compensating for the system nonlinearity, where the controller gains are continuously updated with the change of the system operating conditions, provide a relatively fast response to the changes of operating conditions. A major problem with this method is that the performance depends on the model of the wind turbines linearized at the specific operating points. Also, it is difficult to design the scheduling function updating the controller gains at the different operating points.

In this paper, a novel pitch angle control strategy using hybrid fuzzy logic control is proposed for regulating the turbine output power and the generator speed in the full-load region. For the fuzzy inputs, the power output of generator and the rotor speed instead of the wind speed are adopted, which eliminates need of an expensive anemometer. In addition, with the control variables power output, speed of the generator, the wind turbine is well controlled to maintain it's speed and power output at the rated values without the ripple components.

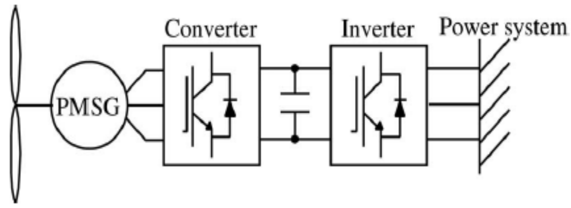


Figure 2. Gearless WECS using PMSG.

II. METHODS AND MATERIAL

1. Wind Energy Conversion System

A. System Configuration

The system arrangement of the gearless WECS system is shown in Fig. 2. Wind energy output of the wind turbine is sent to the PMSG via mechanical interconnection. Rotor speed of the PMSG is adjusted using pulse width modulation (PWM) converter in order to obtain maximum power. Using side by side connected generator-side rectifier and grid-side inverter the power output from PMSG is given to the grid.

B. Wind Turbine Model

Wind turbine power output P_W and wind turbine torque T_w are described by the following equations:

$$P_w = 0.5C_p(\lambda,\beta)\rho\pi R^2 V_w^3 \quad \text{... (1)}$$

$$T_w = 0.5C_p(\lambda,\beta)\rho\pi R^3 V_w^2/\lambda \quad \text{... (2)}$$

where V_w is the wind speed, ρ is the air density, R is the radius of the wind turbine, C_p is the wind turbine power coefficient, $\lambda = \omega_\omega R/V_\omega$ is the tip-speed ratio, ω_ω is the angular rotor speed of the wind turbine and, β is the pitch angle. C_p is described by the following equations:

$$C_p = 0.22(\frac{116}{5} - 0.4\beta - 5)exp^{\frac{-12.5}{\Gamma}} \quad \text{... (3)}$$

$$\Gamma = \frac{1}{(1/(\lambda+0.08\beta))-(0.035/(\beta^3+1))} \quad \text{... (4)}$$

The output power characteristics of the wind turbine are depicted in Fig. 3. Here

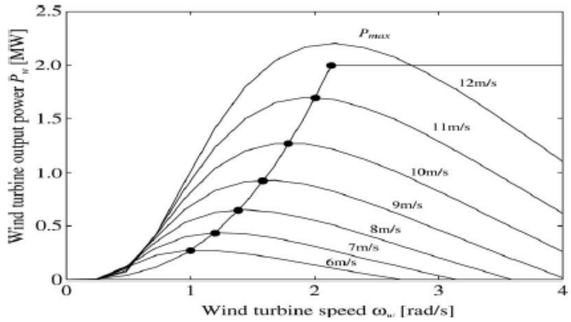


Figure 3. output characteristics of wind turbine

C. PMSG Model

Basically, the mass model of a PMSG is the same as that of a permanent magnet synchronous motor (PMSM). The voltage and torque equations of the PMSM in the $d - q$ reference frames are given by the following equations:

$$v_d = R_a i_d + L_d \frac{di_d}{dt} - w_e L_q i_q \quad \text{... (5)}$$

$$v_q = w_e L_d i_d + R_a i_q + L_q \frac{di_q}{dt} - w_e K \quad \text{... (6)}$$

$$T_e = p\{K i_q + (L_d - L_q) i_d i_q\} \quad \text{... (7)}$$

where v_d and v_q are the dq-axis voltages, i_d and i_q are the dq-axis currents, R_a is the stator resistance, L_d and L_q are the dq-axis inductances, w_e is the generator rotational speed, K is the permanent magnetic flux, and p is the number of pole pairs. Electromagnetic torque T_e should be negative to start generating operation.

2. Conventional Pitch Angle Controllers

In strong wind speeds, the turbine performance is regulated or limited effectively by means of controlling the pitch angle of the blades. To put the blades into the necessary position, pitch servos are employed which may be hydraulic or electrical systems. The pitch angle reference, β_{ref} , is controlled by the input values, Generator power. The error signal of the generator power is sent to a PI controller. The PI controller produces the reference pitch angle β_{ref}.

A. PI/PID Controllers

The conventional pitch control strategy uses the PI/PID controllers to regulate the rotor speed or turbine output power [5], [6]. In the partial-load operation, β_{ref} is fixed at zero and the maximum power point tracking (MPPT) method is applied, so that the energy conversion coefficient is maximized in the partial-load region. In the full-load region, the pitch controller is activated to regulate the generator output power or speed to follow their reference values. To design the PI/PID controller, the nonlinear dynamics of wind turbines is linearized at a specific operating point ($\omega_{rop}, \beta_{op}, v_{wop}$) at which the turbine and generator torques are assumed to be the same.

As aforementioned, when the operating point is changed, the PI controller gains need to be redesigned to maintain the system dynamic response and stability.

B. PI Controller with Gain Scheduling

To improve the control performance of the nonlinear system, the PI controller with the gain scheduling is used. The gain scheduling for the pitch control is to compensate for the changes of the sensitivity of the aerodynamic torque to the pitch angle.

C. Fuzzy Logic Control

The FLC, in which the design of the controller is based on human experience through a set of the empirically determined design rules, has been used for controlling the pitch angle [7]. The generator output power and wind speed are assigned as the control inputs of the FLC. The advantage of this method is that the parameters of the wind turbine system do not need to be known accurately. However, this method requires the wind speed information.

3. Proposed Pitch control scheme based on Hybrid Fuzzy logic control

The block diagram of the proposed pitch angle control based on the fuzzy logic is shown in Fig. 4. In the partial-load region, the power reference of the wind turbine P_{ref} is determined by the MPPT control strategy, which is expressed as [5], [8].

$$P_{ref} = K_{opt} * w_r^3 \qquad \dots (8)$$

where $$K_{opt} = 0.5 * \rho\pi C_{p\,max} \frac{R^5}{\lambda_{opt}^3} \qquad \dots (9)$$

and the maximum power coefficient $C_{p\,max}$ corresponds to the optimal tip-speed ratio λ_{opt} , with a zero-pitch angle. In the high-wind-speed region, the P_{ref} is selected as the rated power of wind turbines. To find the pitch angle reference β_{ref}, the design process for a fuzzy logic controller (FLC) consists of determining the inputs, setting up the rules and converting the results of the fuzzy rules into the output signal which is known as defuzzification.

For this control scheme, the error in the generator power ΔP, the variation of the power error $\delta(\Delta P)$, and the rotational speed w_r are considered as the controller inputs, in which the ΔP and $\delta(\Delta P)$ are defined as

$$\Delta P(k) = P_g(k) - P_{ref}(k) \qquad \dots (10)$$

$$\delta(\Delta P) = \Delta P(k) - \Delta P(k-1) \qquad \dots (11)$$

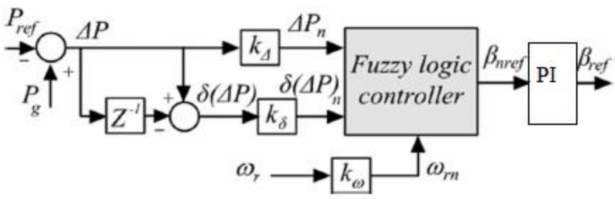


Figure 4. Block diagram of pitch control system using Hybrid FLC

The pitch angle reference is considered as a controller output. To design the fuzzy sets of the inputs and output, the triangular membership functions with the overlap are used, which are illustrated in Fig. 5. The linguistic variables are represented by Negative Big (NB), Negative Medium Big (NMB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), Positive Medium Big (PMB), and Positive Big (PB). The control rules are derived from the experience and knowledge on the control system. The fuzzy mapping of the input variables to the output is expressed by the following rules:

R_i: IF $w_r(k)$ is A_i and $\Delta P(k)$ is B_i and $\Delta P(k-1)$ is C_i THEN β_{ref} is D_i.

Where A_i, B_i, and C_i are the fuzzy subset, D_i is a fuzzy singleton. The fuzzy rules are given in Table 1.

In this paper, the fuzzy with the Sugeno type is applied for the inference mechanism [9], [10]. Each rule is weighted by the weighting factor w_i of the rule, which is obtained from the minimum operation as

$$W_i = \min\{\mu_{\Delta p}(\Delta P), \mu_{\delta\Delta p}(\delta(\Delta P)), \mu_w(w_r)\} \quad \dots (12)$$

Where $\mu_{\Delta p}(\Delta P), \mu_{\delta\Delta p}(\delta(\Delta P)), and\ \mu_w(w_r)$ are the triangular membership functions of the ΔP, $\delta(\Delta P)$, and w_r.

The weighted average of every rule output, which expresses the variation of the pitch angle reference β_{ref} is calculated as [10]

$$\beta_{n\,ref} = \frac{\sum_{i=1}^{N} W_i D_i}{\sum_{i=1}^{N} W_i} \quad \dots (13)$$

Where N is the total number of the rules and D_i is the coordinate corresponding to the respective output or consequent membership function.

Table 1. Rules of FLC

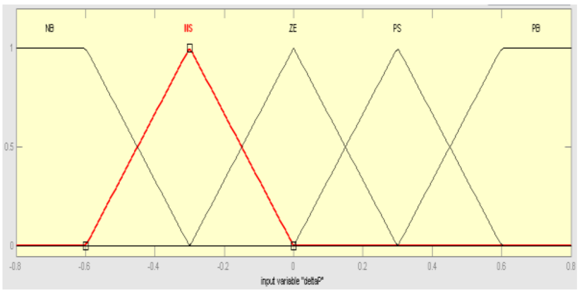
w_r		PS					PM					PB				
ΔP		NB	NS	ZE	PS	PB	NB	NS	ZE	PS	PB	NB	NS	ZE	PS	PB
$\delta\Delta P$	NB	NB	NB	NB	NB	NMB	NS	NS	NS	PM	PMB	PS	PS	PM	PMB	PB
	NS	NB	NB	NB	NMB	NMB	NS	NS	ZE	PM	PMB	PS	PS	PMB	PMB	PB
	ZE	NB	NB	NMB	NMB	NM	NS	ZE	ZE	PM	PMB	PS	PM	PMB	PB	PB
	PS	NB	NMB	NMB	NM	NM	NS	ZE	ZE	PMB	PMB	PM	PM	PB	PB	PB
	PB	NMB	NMB	NM	NM	NM	ZE	ZE	PS	PMB	PMB	PM	PM	PB	PB	PB

Table 2. Wind Turbine parameters for simulation

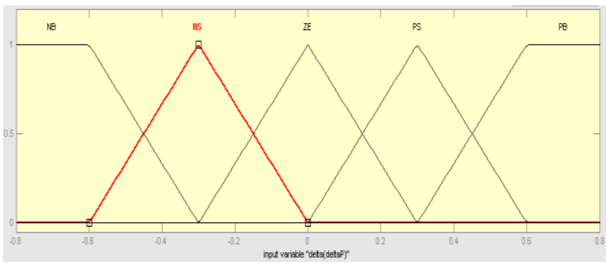
Rated Power	2 MW
Blade Radius	38.3 m
Air density	1.225 kg/m^3
Max. power conv. Coefficient	0.411
Cut in speed	3 m/s
Cut out speed	25 m/s
Rated wind speed	12 m/s
Blade Inertia	$6.3*10^6$ kg.m^2

Table 3. PMSG parameters for simulation

Rated Power	2 MW
Grid Voltage	690 v
Stator voltage/frequency	690v/16.6HZ
Stator resistance	0.008556Ω
Stator inductance	0.00359H
Generator inertia	48000 $kg.m^2$



(a)



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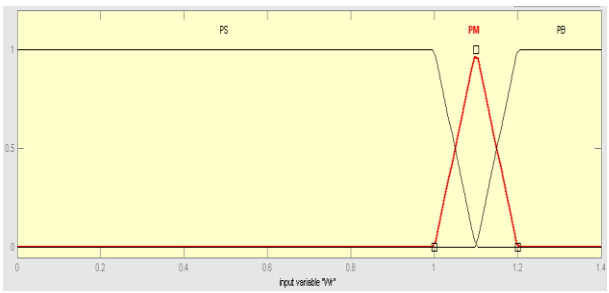

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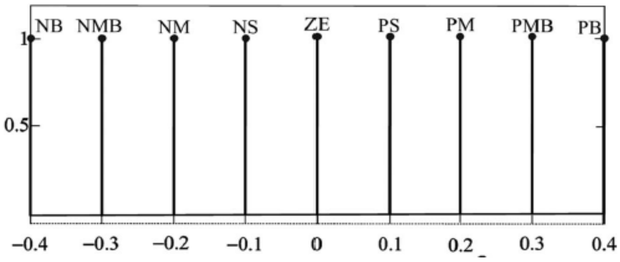


(d)

Figure 5. Membership functions of FLC for (a) error of generator output power. (b) Variation of power error. (c) Rotational speed. (d) Pitch angle reference

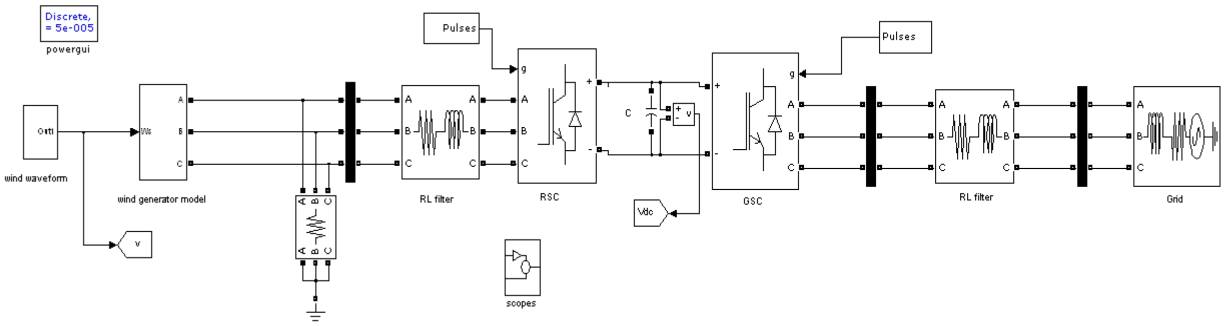


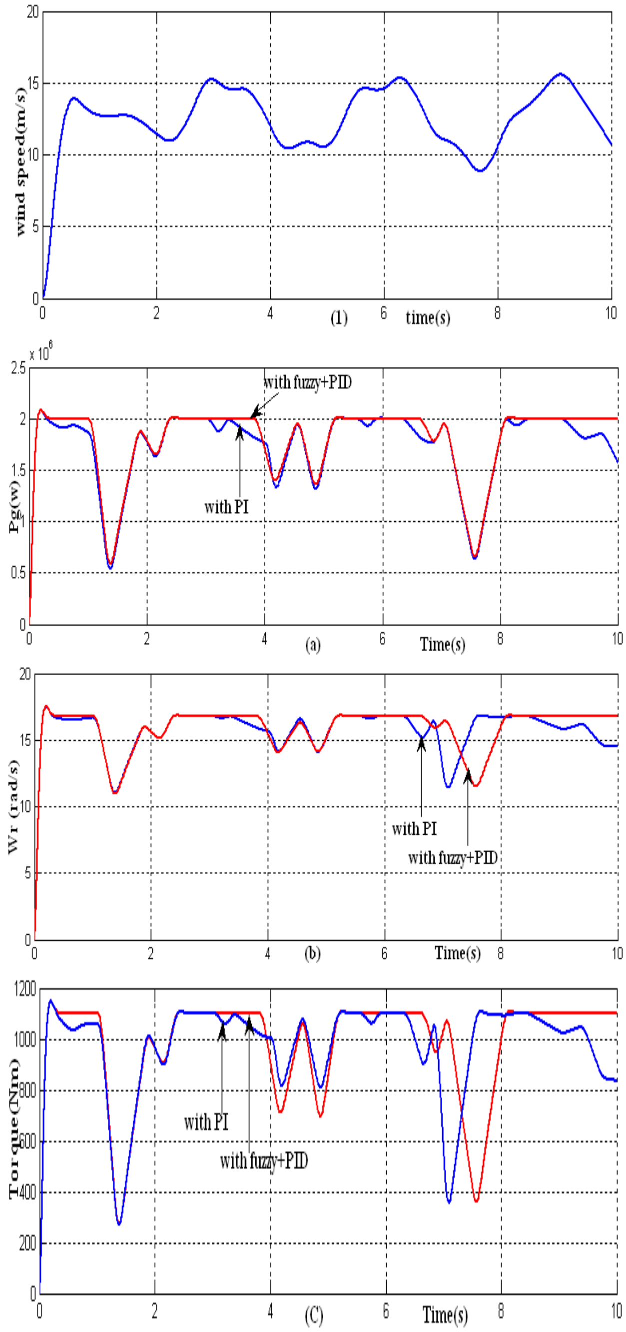
Figure 6. Simulink Diagram

III. RESULTS AND DISCUSSION

Simulation Results

To verify the validity of the proposed method, the simulation has been performed for 2-MW PMSG wind power system as shown in fig. 6. The parameters of the wind turbine and PMSG are listed in Tables 2 and 3, respectively. The sampling time for FLC is 2ms. The pitch angle rate is limited to $\pm 10° \, s^{-1}$. Fig. 7(1) shows the wind speed, of which the rated value is 12 m/s. By this input wind speed, the turbine is operated in the full-load region. Fig. 7 shows the performance comparison of the two pitch angle controllers; (a) for the PI controllers with the fixed gains ($K_p = 3$ and K_I = 30); (b) for the proposed with $K_\Delta = 0.5 \times 10^{-6}$, $K_\delta = 0.5 \times 10^{-2}$, and $K_w = 6 \times 10^{-2}$, $K_\beta = 100$. For the PI/PID controllers, only one variable of either the generator power or speed is used as a control input, whereas in the proposed hybrid fuzzy logic control method, both the generator power and the rotor speed are involved for the control input variables. Fig. 7(a) shows the generator power which is not well maintained at the rated value and has the high ripple components with the PI/PID controllers, whereas it is kept almost at the rated value by the proposed pitch control strategy. The average generator power for the two methods in the full-load region is evaluated, in which the proposed method gives higher output power than that of the PI controller. Regarding the generator speed and torque, the similar performance is shown in Fig. 7(b) and (c), respectively. Fig. 7(d) shows the power conversion coefficient, which is kept at the maximum value of 0.411 for a variable speed region, however, it is decreased in the full-load region according to the increase of the pitch angle as shown in Fig. 7(e).

To investigate the performance of the PI controllers and the Hybrid FLC at the different operating point, the rated wind speed which classifies the partial and full-load regions is set as 14 m/s, differently from the previous case of 12 m/s. Fig. 8 shows the results of the pitch control for the PI controller and the proposed fuzzy controller, at the rated wind speed of 14 m/s. The gain parameters for both the PI/PID controllers and the membership function of the fuzzy logic control are the same as those of the prior case. The wind speed pattern is the same for both cases as shown in Fig. 11(1). All of the pitch angle control methods can limit the generator power and rotor speed to their rated values. However, the pitch angle control employing the proposed hybrid fuzzy control method gives better performance than those of the PI control. Fig. 8(a)–(c) shows the generator output power, rotor speed, and mechanical torque, respectively, where with the same controller gains, the PI controller at the mean wind speed of 14 m/s, cannot give as good results as that designed at the mean wind speed of 12 m/s. Meanwhile, they are kept mostly at the rated value in the high wind- speed region with the proposed control scheme. Therefore, to guarantee that the system works well at every operating point, these gains should be redesigned. On the other hand, although the operating point is changed, the pitch angle control using the proposed hybrid FLC method still gives good performance. It is evaluated that in the high-wind-speed region, the average generator output power with the proposed method is higher than that of using the PI controller.



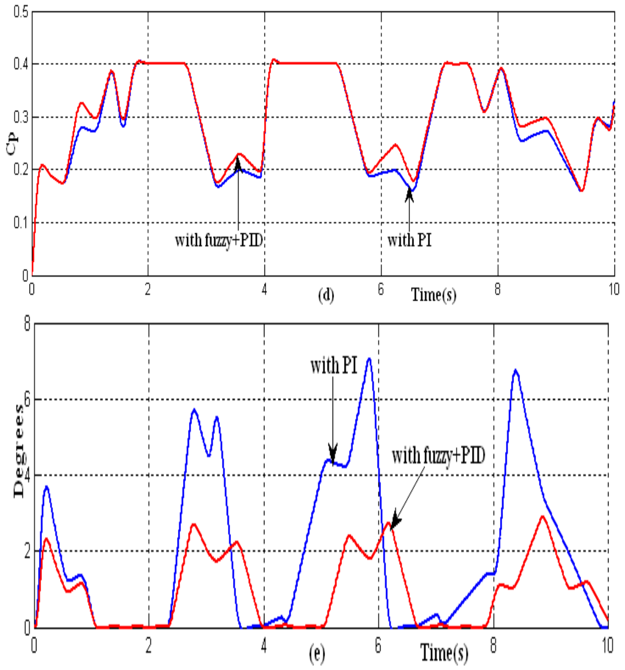
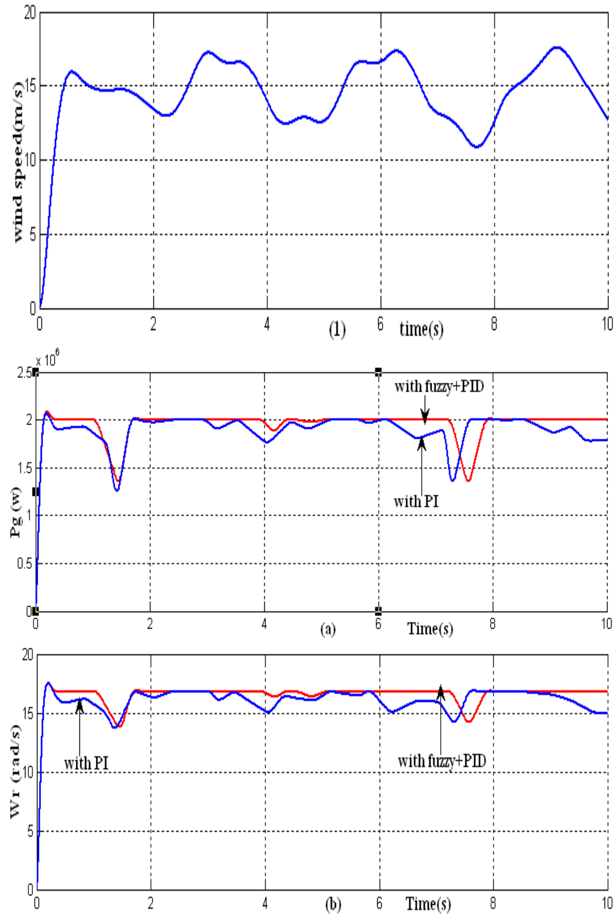


Figure 9. Simulation results for PI controller, and proposed hybrid FLC at the mean wind speed of 12 m/s. (a) Generator powers. (b) Rotor speeds. (c) Mechanical torques. (d) Power conversion coefficients. (e) Pitch angles.



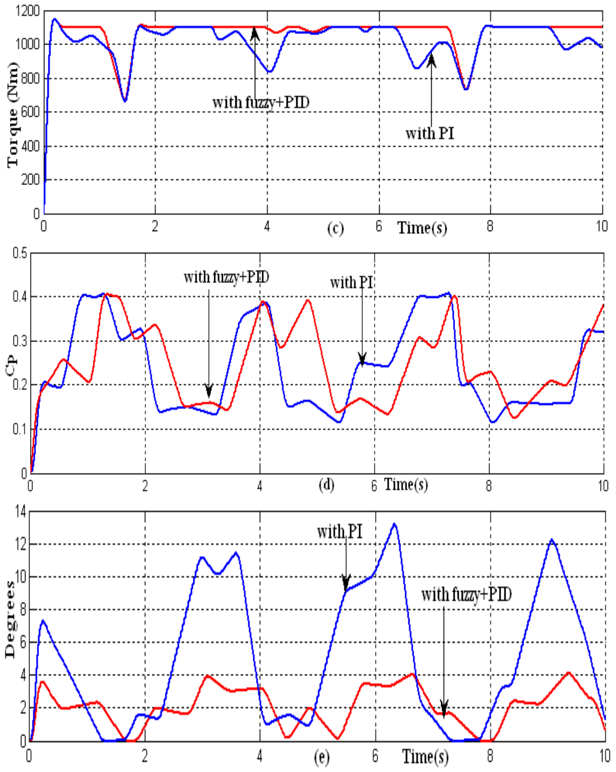


Figure 8. Simulation results for PI controller, and proposed hybrid FLC at the mean wind speed of 14 m/s. (1)Wind speeds. (a) Generator powers. (b) Rotor speeds. (c) Mechanical torques. (d) Power conversion coefficients. (e) Pitch angles.

IV. CONCLUSION

In this paper, a novel Hybrid Fuzzy logic Pitch angle control has been employed to PMSG wind turbine system to regulate the turbine output power and the turbine speed at their ratings. The nonlinear properties of pitch system have been derived using small signal analysis to develop the control scheme. The generator output power and rotational speed are selected as the input variables to the Hybrid FLC. The simulation results shows that the proposed pitch angle controller can limit the turbine output power and speed at the rated values satisfactorily at high-wind-speed regions.

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