Pitch Angle Controlling of Wind Turbine System Using Proportional-Integral/Fuzzy Logic Controller

Rupendra Kumar Pachauri, Harish Kumar, Ankit Gupta and Yogesh K. Chauhan

Abstract Blade pitch angle and tip speed ratio (TSR) control approaches are very important in Wind Turbine (WT) to achieve a constant output torque for stability of WT operation. Therefore, accurate and effective control techniques are investigated and designed to supply constant output torque to the Permanent Magnet Synchronous Generator (PMSG). Furthermore, two controlling approaches, i.e. Proportional-Integral (PI) and Fuzzy Logic (FL) based blade pitch angle and TSR control are implemented, and their performance is investigated in terms of torque stability and response time. The complete system is modeled in MATLAB/Simulink environment. The performance of the system with these control techniques are investigated under variable wind speed conditions. The performance of both the systems is found satisfactory, but system with FLC shows better performance as compared to PI controller.

Keywords Fuzzy logic controller · Blade pitch angle control · Permanent magnet synchronous generator · Tip speed ratio · Wind turbine

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1 Introduction

The role of electrical energy is very important for developing a country. The shortage of fossil fuels e.g. petrol, diesel, coal and gas etc. is experienced globally due to exponential increase in the rate of energy consumption. It is forced to explore more sustainable energy resources [1]. In this context, the WT and photovoltaic systems are commonly used in various applications e.g. water pumping irrigation and rural electrification etc. Wind power technology has experienced a notable escalation, and progressing from last three decade. Today, WT is found as one of the best growing RE source [1].

The authors have formulated a mathematical model of WT and the mechanical torque produced by the WT is obtained in [2]. The predefined pitch angle WT model has been used for power generation with permanent magnet synchronous generator (PMSG). The authors [3] analysed the dynamic model of PMSG based on Wind Energy Conversion System (WECS). In [4], the authors proposed a wind turbine generator system (WTGS) connected with a variable speed turbine generator. Apart from the generator, the authors also investigated that WTGS contains of three parts i.e. wind turbine, drive train and PMSG. WT can be categorized into two kinds based on the axis in which it rotates namely horizontal axis wind turbines (HAWT) and vertical axis WTs (VAWT). A WT with a blade pitch angle control using the fuzzy logic (FL) to obtain the maximum output power is designed [5]. The authors have also shown that implementation of FL based pitch angle control to the WT is most suitable for the low level wind speed regions.

With the motivation of above literature review, the research aspect of this paper is to investigate and comparative analysis of PI and FL controller based blade pitch angle and TSR control for torque optimization of WT system.

2 System Description

The complete system comprises three major parts (a) Wind Turbine (b) Permanent magnet synchronous generator (c) Blade pitch angle and Tip speed ratio controlling schemes (i) Proportional-integral controller (ii) Fuzzy logic controller. The complete system is shown in Fig. 1.

The paper is outlined as follows. In Sect. 3, the WT modeling is presented. In Sect. 4, the mathematical modeling of PMSG is reported. In Sect. 5, the blade pitch angle and tip speed ratio control schemes are discussed in detail. Finally, the results are discussed in Sect. 6 and Sect. 7 concludes the paper.

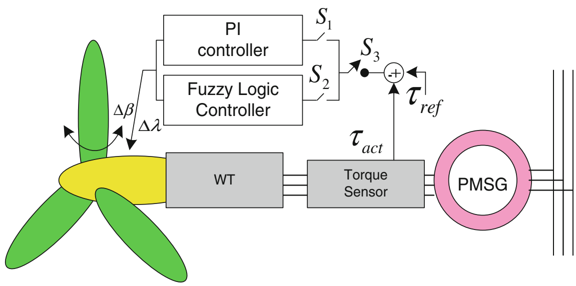

Fig. 1 Schematic diagram of blade pitch angle control of WT-PMSG system

3 Mathematical Modeling of WT

The WT converts the kinetic energy of wind potential into mechanical energy. A WT can function at a steady state speed with changeable blade pitch angle and TSR that allows it to produce the constant power at 50 Hz, which is required for connection with the grid [5]. The power available in the wind is equal to the amount of energy produce per second wind power (P_{wind}), power (P_m) and torque (τ_m) equations of a WT are given by Eq. (1) as,

$$P_{wind} = \frac{1}{2} A\rho V_w^3, \quad P_m = 0.5\rho A C_p V_w^3, \quad \tau_m = 0.5\rho A C_p V_w^2 \frac{R}{G\lambda} \tag{1}$$

where, A is the swept area of rotor blades, ρ is the air density, V_w is wind speed, C_p is coefficient of performance, R is rotor radius, G is gear ratio and λ is TSR. The power coefficient characteristic is highly non-linear in nature and reflects the aerodynamic behaviour of WT. The C_p is expressed in Eq. (2) as,

$$C_p(\lambda, \beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{\frac{-C_5}{\lambda_i}} + C_6\lambda, \quad \frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{2}$$

where, C_1, $C_2 \ldots C_6$ are coefficients, β is blade pitch angle and λ_i is initial TSR. The TSR (λ) is expressed in Eq. (3) as the ratio between the speed of the tips of the blades of a WT and the wind speed.

$$\lambda = \frac{V_{TIP}}{V_W} = \omega \cdot R / V_w \tag{3}$$

where, ω is the rotor angular velocity (rad/s). The coefficient of performance C_p, is expressed as the fraction of energy extracted by WT of the total energy that would have followed through the area swept by the rotor. The coefficient of power is expressed in Eq. (4) [6] as,

$$C_p(\lambda) = 0.5176\left(\frac{116}{\lambda} - 9.06\right)e^{\frac{-21}{\lambda}+0.735} + 0.0068\lambda \tag{4}$$

4 Mathematical Modeling of PMSG

The PMSGs are utilized for various commercial purposes in wide range. The PMSGs are commonly used to convert the mechanical power output of turbines i.e. steam turbines, wind turbines etc. into electrical power for the intended system. The WT and the generator rotate in synchronism with the same shaft without gear assembly. The mathematical model of the PMSG in the state space equation form is given by Eq. (5) [6] as,

$$\frac{di_q}{dt} = \frac{(-R_s i_q + \omega_e(L_{qs} + L_{ls})i_d + u_q)}{L_{qs} + L_{ls}}, \quad \frac{di_d}{dt} = \frac{(-R_s i_d + \omega_e(L_{qs} + L_{ls})i_q + u_d)}{L_{ds} + L_{ls}} \tag{5}$$

where, R is the stator resistance, L_q and L_d are the inductances of the generator along d and q axis and L_{ls} is the leakage inductance of the generator. The electrical speed (ω_e) (rad/s) of the generator and electromagnetic torque equation of PMSG are expressed in Eq. (6) as,

$$\omega_e = p\omega_g, \quad \tau_{em} = 1.5p((L_{ds} - L_{ls})i_d i_q + i_q\psi_f) \tag{6}$$

where, i_d and i_q are the currents along d and q axis, ψ_f is the permanent magnetic flux, p is the number of pole pairs and τ_{em} is the electromagnetic torque of the generator.

5 Blade Pitch Angle and TSR Control Strategies

For controlling the torque using blade pitch angle and TSR, following two controllers namely PI and FLC are considered as,

5.1 Proportional—Integral Controller

The PI controller is a control which has feedback mechanism which is commonly used in industrial control operations [7]. The optimum combination of proportional and integral gain increases the speed of the response and also to minimize the steady state error. The PI controller equation is expressed in Eq. (7) as,

$$u(t) = K_p e(t) + K_i \int e(t)dt \quad (7)$$

where, K_p and K_i are proportional and integral gain, and used to control the response of the system. The input of the PI controller is the error between τ_{ref} and τ_{actual} and the output is change in blade pitch angle or TSR [8, 9].

5.2 *Fuzzy Logic Controller*

Recently, FLCs are introduced for blade pitch angle control for WT. These controllers are robust and advantageous as their design procedure does not require exact model information. Their major goal is to implement human knowledge/information in the form of a program [10, 11]. The main parts of a FLC are fuzzification, rule base, inference and defuzzification as shown in Fig. 2,

Both the inputs i.e. error (e) and change of error (ce) are shown in Eq. (8) as,

$$e(k) = \tau_{ref}(k) - \tau_{actual}(k),\ ce(k) = e(k) - e(k-1) \quad (8)$$

The rule base for FLC are shown in Table 1 as,

For the FL controller the output is the change in pitch angle or TSR. This generated pitch angle targets the WT to produce the optimal torque. The membership functions for both inputs and output are shown in Fig. 3a–c as,

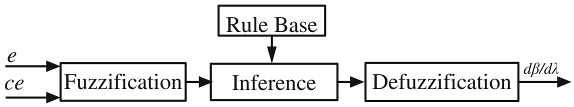

Fig. 2 Block diagram of FLC

Table 1 Rule base for FLC

e/ce	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NM	NM	NS	NS	ZE
NM	NB	NM	NM	NS	NS	ZE	PS
NS	NB	NM	NM	NS	ZE	PM	PM
ZE	NM	NS	NS	ZE	PM	PM	PB
PS	NS	NS	ZE	PS	PS	PM	PM
PM	NS	ZE	PS	PS	PM	PM	PB
PB	ZE	PS	PS	PM	PM	PB	PB

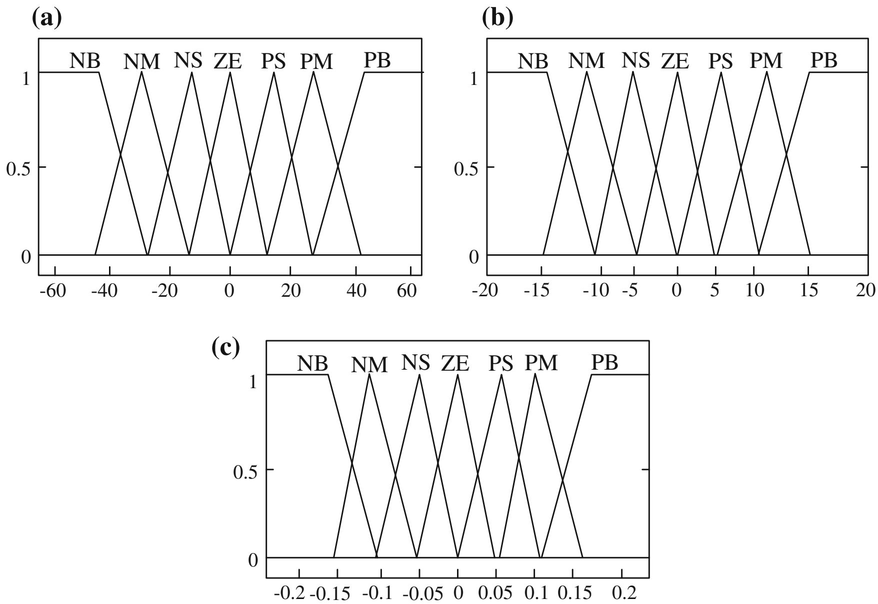

Fig. 3 Membership functions of fuzzy logic controller. **a** Input variable "e". **b** Input variable "ce". **c** Output variable "dβ/dλ"

6 Results and Discussion

The operating parameters of WT and PMSG are given in Appendix. The performance of blade pitch angle and TSR control systems is analyzed for both PI and FLC based controllers under desired wind speed condition using pitch angle, turbine torque, TSR and PMSG stator currents, rotor speed and electromagnetic torque.

The wind speed is varied in the range of 10–17 m/s, as shown Fig. 4. Both the cases of step increase and decrease in wind speed from reference point are considered. This pattern of wind speed variation is applied to both the systems with PI

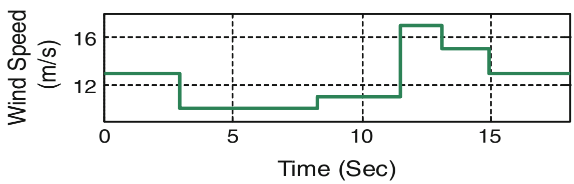

Fig. 4 Variation of wind speed

and FLC for blade pitch angle and TSR controlling. The transient response of blade pitch angle and TSR controlling using PI and FL controllers are shown in Figs. 5 and 6.

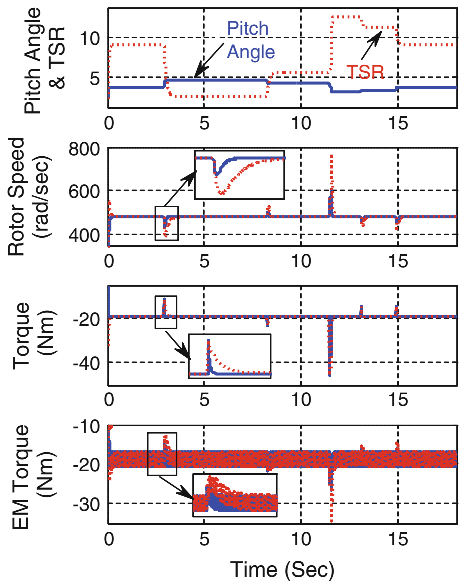

Fig. 5 Transient response of pitch angle and TSR controlling using PI controller

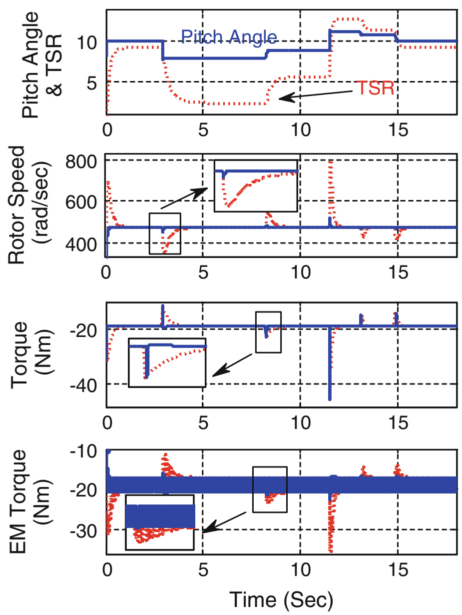

Fig. 6 Transient response of pitch angle and TSR controlling using FL controller

Table 2 Comparison of PI and FLC based system for blade pitch angle and TSR control

Parameters	Settling time (s)			
	PI controller		FL controller	
	Pitch angle	TSR	Pitch angle	TSR
Pitch angle/TSR	1.17	0.689	0.039	0.03
Torque	0.95	0.225	0.059	0.02
Rotor speed	0.94	0.319	0.289	0.09
EM torque	0.87	0.369	0.269	0.06

6.1 Transient and Comparative Analysis

The comparison of PI controller and FLC operated system is obtained on the basis of settling time for pitch angle, TSR, torque, rotor speed and electromagnetic torque developed. It is clear from Table 2 that FLC based system settles quickly as compared to PI based system as,

In Figs. 5 and 6 shows the blade pitch angle and TSR control by using PI and FL controller for defined wind speed variation. It is observed that for obtaining constant torque, the variation and settling time of pitch angle is less compared to variation in TSR. As a result of blade pitch angle and TSR variation, the effects of wind speed variation are compensated and the rotor speed, WT torque and EM torque are found almost constant. From above transient study, it is observed that the FL based controller has less settling time than PI controller. The comparative study of these parameters is summarised in Table 2.

7 Conclusions

In this paper, a study of WT based wind energy conversion system has been carried out. The real value system model of WT along with the system components are built in MATLAB/Simulink environment. With the simulation of the complete WECS using MATLAB/Simulink model, all the results have been obtained for PI & FLC for both blade pitch angle and TSR control and a their comparative study is also reported.

The simulation results shows that the reference torque is conveniently achieved by either adjusting the blade pitch angle or by TSR control using PI & FLC. By analyzing the output of FLC and PI, it is observed that FLC is better than PI based controller for torque control of the WT.

Appendix

Number of blades = 3, Blade radius (R) = 4.5 m, Gear ratio (G) = 40, Air density (ρ) = 1.2 kg/m^3, Wind speed (v_w) = 10–17 m/s, Power Coefficient (C_p) = 0.45, C_1 = 0.5176, C_2 = 116, C_3 = 4, C_4 = 5, C_5 = 21, C_6 = 0.0068, Stator Phase Resistance (R_s) = 0.4250 Ω, Inductance (L_d, L_q) = 0.0084, 0.0084 H, Inertia (J) = 0.001469 kg m^{2,} Friction factor (F) = 0.0003035 N m s, Pole pairs = 4, K_p = 0.02, K_i = 3.0.

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