Pitch Angle Control for Variable Speed Wind Turbines

Jianzhong Zhang, Ming Cheng, Zhe Chen, Xiaofan Fu

***Abstract*--Pitch angle control is the most common means for adjusting the aerodynamic torque of the wind turbine when wind speed is above rated speed and various controlling variables may be chosen, such as wind speed, generator speed and generator power. As conventional pitch control usually use PI controller, the mathematical model of the system should be known well. A fuzzy logic pitch angle controller is developed in this paper, in which it does not need well known about the system and the mean wind speed is used to compensate the non-linear sensitivity. The fuzzy logic control strategy may have the potential when the system contains strong non-linearity, such as wind turbulence is strong, or the control objectives include fatigue loads. The design of the fuzzy logic controller and the comparisons with conversional pitch angle control strategies with various controlling variables are carried out. The simulation shows that the fuzzy logic controller can achieve better control performances than conventional pitch angle control strategies, namely lower fatigue loads, lower power peak and lower torque peak.**

***Index Terms*--Blade aerodynamic, Fatigue load, Fuzzy logic control, Pitch angle, Wind turbine**

I. Introduction

RECENT years, a fast growing in wind energy is experienced in whole world. At the end of 2006, the installed capacity of wind farms in China reaches 2600 MW, which is increased by 105% compared with 2005. Wind power may become China's third major power supply by 2020, with an expected installed capacity of 40 GW.

Pitch-adjusting variable-speed wind turbines have become the dominating type of yearly installed wind turbines in recent years. There are usually two controllers for the variable-speed wind turbines which are cross-coupled each other, shown as in Fig. 1. In low wind speed below rated value, the speed controller can continuously adjust the speed of the rotor to maintain the tip speed ratio constant at the level which gives the maximum power coefficient, and then the efficiency of the turbine will be significantly increased. Pitch angle regulation is required in conditions above the rated wind speed when the rotational speed is kept constant. Small changes in pitch angle

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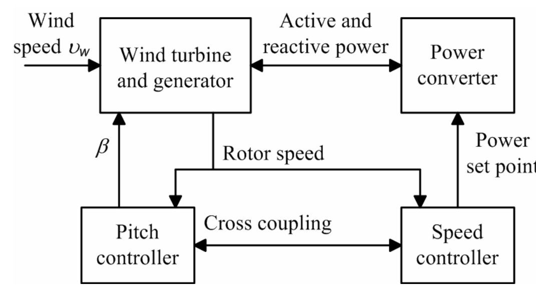


Fig. 1 Structure of a model of variable-speed wind turbine

can have a dramatic effect on the power output. The purpose of the pitch angle control might be expressed as follows [1-3]:

1) Optimizing the power output of the wind turbine. Below rated wind speed, the pitch setting should be at its optimum value to give maximum power.
2) Preventing input mechanical power to exceed the design limits. Above rated wind speed, pitch angle control provides a very effective means of regulating the aerodynamic power and loads produced by the rotor.
3) Minimizing fatigue loads of the turbine mechanical component. It is clear that the action of the control system can have a major impact on the loads experienced by the turbine. The design of the controller must take into account the effect on loads, and the controller should ensure that excessive loads will not result from the control action. It is possible to go further than this, and explicitly design the controller with the reduction of certain fatigue loads as an additional objective.

The rain-flow counting method is widely used in the analysis of fatigue data which can assess the fatigue life of a structure subject to complex loading. From the view of the cycle counting method during a given time history, simple comparisons of the fatigue life for the turbine components can be carried out.

In this paper, conventional pitch angle control strategy, in which various controlling variables may be used, is discussed. As the conventional pitch control strategy usually uses proportional and integral (PI) controller, the knowledge of the system dynamic is need [4-7]. However, fuzzy logic controller does not need a well known system and is potential for the system contains strong non-linearity. The fuzzy logic control for wind turbines has been proposed in some papers [8-10]. Refs. [8-9] propose a fuzzy logic controller for maximum power point tracking (MPPT) control and Ref. [10] proposes a fuzzy logic pitch angle controller for power system stabilization. In this paper, on the basis of previous three purposes, a fuzzy logic pitch angle controller is designed and analyzed. The simulations and comparisons of the different pitch angle control strategies are carried out and the conclusions are drawn at last.

II. Wind Turbine Modeling

A. *Power Capture of Wind Turbines*

The power in the wind is proportional to the cube of the wind speed and may be expressed as

$$P = 0.5\rho A \upsilon_w^{\ 3} \tag{1}$$

where ρ is air density, A is the area swept by blades and υ_w is wind speed. A wind turbine can only extract part of the power from the wind, which is limited by the Betz limit (maximum 59%). This fraction is described by the power coefficient of the turbine, C_p, which is a function of the blade pitch angle and the tip speed ratio. Therefore the mechanical power of the wind turbine extracted from the wind is

$$P_w = 0.5 C_p(\beta, \lambda)\rho A \upsilon_w^{\ 3} \tag{2}$$

where C_p is the power coefficient of the wind turbine, β is the blade pitch angle and λ is the tip speed ratio. The tip speed ratio is defined as the ratio between the blade tip speed and the wind speed υ_w

$$\lambda = \frac{\Omega R}{\upsilon_w} \tag{3}$$

where Ω is the turbine rotor speed and R is the radius of the wind turbine blade.

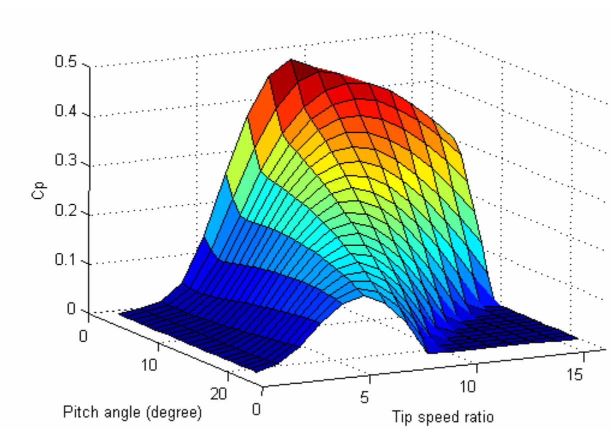


Fig. 2 Power coefficient characteristics

Thus any change in the rotor speed or the wind speed induces change in the tip speed ratio leading to power coefficient variation. In this way, the generated power is affected. Fig. 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, $C_{p.max}$. 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 speed.

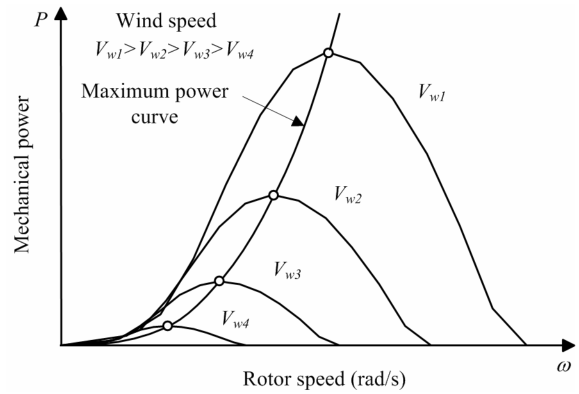


Fig. 3 Mechanical power versus rotor speed characteristics

The typical power control regions of wind turbine are shown in Fig. 4. The turbine starts operating when the wind speed exceeds cut-in wind speed. The power captured by the turbine increases with the wind speed increasing. At the set point of wind speed, the generating power reaches the rated power of the turbine. If the wind speed continues to rise, the generator output power remains constant at the design limit. Due to safety consideration, the turbine is shut down at speeds exceeding cut-out wind speed.

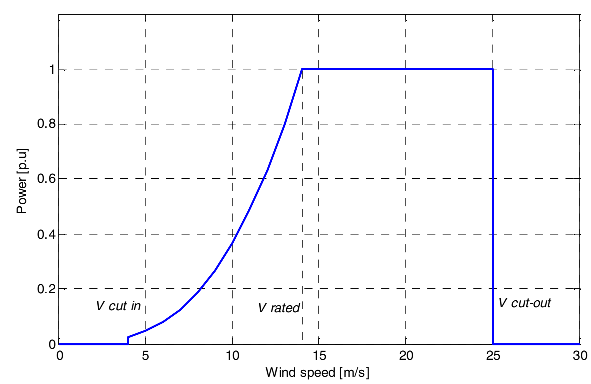


Fig. 4 Power control regions of wind turbines

B. *Blade Aerodynamics*

The wind velocity conditions at a blade cross-section are illustrated in Fig. 5. The velocity components, include the wind speed, the flow factors and rotational speed of the rotor, will determine the angle of attack. Using angle of attack, the forces on a blade element is calculated by means of two-dimensional aerofoil characteristics. Then the blade element momentum (BEM) method can be used to predict the blade forces produced due to the interaction of blades with the wind.

The inflow wind velocity perpendicular to the rotor plane is υ_w. When the wind passes through the rotor plane, this wind speed becomes reduced by an amount $a\upsilon_w$ due to axial interference. The blade rotates at angular velocity Ω. Thus, a blade element at a distance r from the rotor axis will be moving at a speed Ωr in the rotor plane. When the wind passes through the rotor plane and interacts with the moving rotor, a tangential velocity of the wake $a'\Omega r$ is introduced. Then the net tangential flow velocity experienced by the blade element is $(1+a')\,\Omega r$. The resultant relative velocity at the blade is

$$W = \sqrt{\upsilon_w^2(1-a^2) + \Omega^2 r^2 (1+a')^2} \quad (4)$$

where W is the resultant relative velocity at the blade, a and a' is the flow factors and r is the distance of blade element from the rotor axis. The resultant relative velocity gives rise to aerodynamic forces on the blade, therefore a lift force is

$$F_L = \frac{1}{2}\rho c W^2 C_L \quad (5)$$

and a drag force is

$$F_D = \frac{1}{2}\rho c W^2 C_D \quad (6)$$

where C_L is lift coefficients, C_D is drag coefficients and c is the chord length of the blade.

In the pitch-adjusting variable-speed wind turbines, the angle of attack, α, decreases when the pitch angle, β, increases, as shown in Fig. 5. The lift force, F_L, decreases as well and this causes reduction of the mechanical power of the wind turbine. According to the pitch angle control, the initial angle below rated wind speed is the optimized value, β_{opt}. The optimized pitch angle can be defined using the BEM method from the incoming wind and it is in very few degrees around zero. As shown in Fig. 4, the power of the wind turbines will increase at the increasing wind. The wind turbine must be protected against mechanical overloads and possible risk of damages at strong wind. This is achieved by pitching the blades into the position where a part of incoming wind will pass by the wind turbine. The power will be kept at its rated value at this region. By pitching, the thrust is reduced. Fig. 6 shows the curve of the pitch angle versus incoming wind speed which is computed with use of the BEM method for the given 1.5 MW wind turbine.

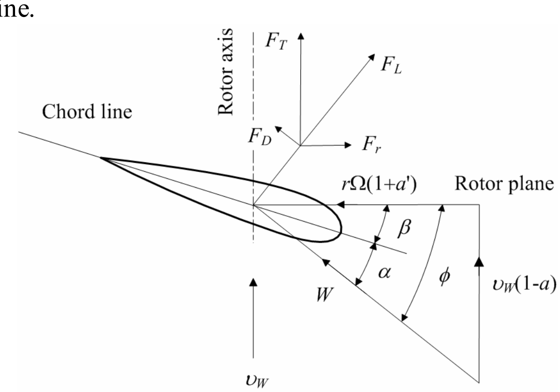


Fig. 5 Blade element velocities and force at a blade dross-section.

III. Conventional Pitch Angle Control

Adjusting the pitch angle of the blades, as shown in Fig. 2, provides an effective means of regulations or limiting turbine performance in strong wind speeds. To put the blades into the necessary position, pitch servos are employed which may be hydraulic or electrical systems. During normal operation, blade pitch adjustments with rotational speeds of approximately 5-10º/s are expected [11]. Here the chosen pitch rate is 8º/s which avoids excessive loads during normal regulation procedures.

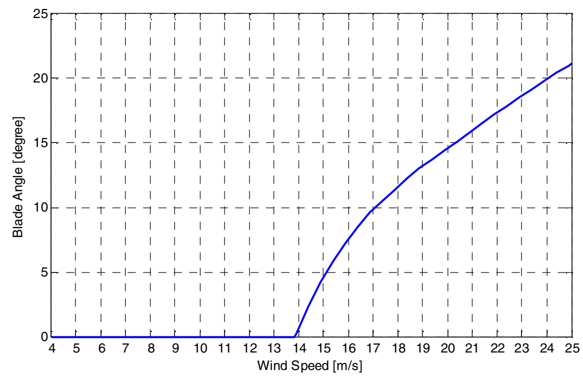
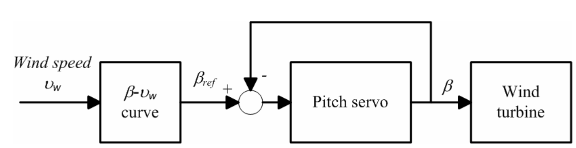


Fig. 6 Generic blade pitch angle

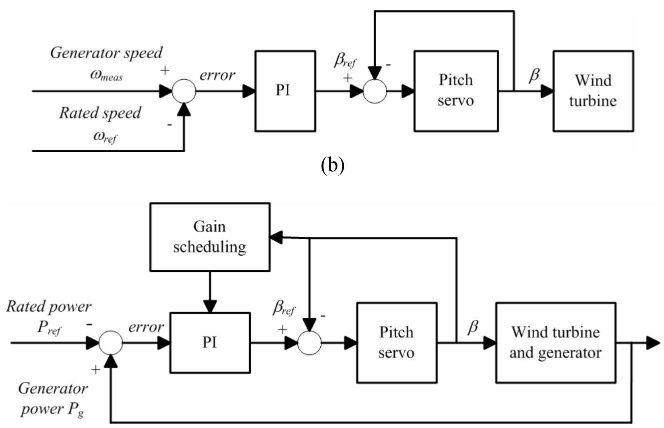
The conventional blade pitch angle control strategies are shown in Fig. 7. The pitch angle reference, β_{ref}, is controlled by the input values, which may be as follows:

1) Wind speed, as shown in Fig. 7(a). Ideally, the pitch angle reference can be obtained from the curve of the pitch angle versus wind speed, as shown in Fig. 6. This control strategy is simple as the wind speed is directly measured. However, this is not an appropriate procedure, since it is not possible to measure the wind speed precisely.
2) Generator rotor speed, as shown in Fig. 7(b). The controlling rotor speed is compared with its reference. The error signal is then sent to the PI controller and produces the reference value of the pitch angle, β_{ref}.
3) Generator power, as shown in Fig. 7(c). The error signal of the generator power is sent to a PI controller. The PI controller produces the reference pitch angle β_{ref}. The non-linear variation of the pitch angle versus wind speed for large wind speeds, illustrated in Fig. 6, implies the necessity of a non-linear control. When the wind speed is close to the rated, the sensitivity of aerodynamic torque to pitch angle is very small. Thus a much larger controller gain is required here than at higher wind speeds, where a small change in pitch can have a large effect on torque. Frequently the torque sensitivity changes almost linearly with pitch angle, and so can be compensated by varying the overall gain of the controller linearly in inverse proportion to the pitch angle. Such a modification gain with operating point is termed as gain scheduling [5].

The conventional pitch angle control strategy with gain scheduling performs well when the system dynamic is not strong. However, the sensitivity of aerodynamic torque to pitch angle varies in a different way which is treated as linear variation in gain scheduling, and because of its effect on turbine dynamics which couples strongly with the pitch controller, it may be necessary to modify the gain scheduling further to ensure good performance in all winds.



(a)



(c)

Fig. 7 Pitch angle control strategy. (a) Wind speed; (b) generator rotor speed; (c) generator power.

IV. Fuzzy Logic Control

Rule based fuzzy logic controllers are useful when the system dynamics are not well known or when they contain significant non-linearities, such as the un-stationary wind contains large turbulence. The advanced control strategies are more favor as reducing fatigue loads is one of the control motivations.

Fuzzy logic controllers apply reasoning, similar to how human beings make decisions, and thus the controller rules contain expert knowledge of the system. The big advantages of fuzzy logic control when applied to a wind turbine are that the turbine system neither needs to be accurately described nor does it need to be linear. The design process for a fuzzy logic controller consists of (i) determining the inputs, (ii) setting up the rules and (iii) designing a method to convert the fuzzy result of the rules into output signal, known as defuzzification.

This paper proposed a new fuzzy logic controller for the pitch control where one of the motivations of the controller is to reduce the fatigue loads. The fuzzy logic control system is shown in Fig. 8. The input and output membership functions are shown in Fig. 9. Triangular symmetrical membership functions are suitable for the input and output, which give more sensitivity especially as variables approach to zero value. The width of variation can be adjusted according to the system parameters.

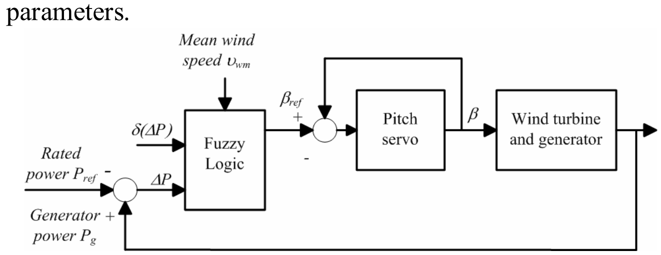


Fig. 8 Fuzzy logic control strategy

As shown in Fig. 8, the proposed fuzzy logic controller is based on the power deviation from its reference value ΔP, its variation during a sampled time $\delta(\Delta P)$ as follows:

$$\begin{cases} \Delta P = P_{ref} - P_g \\ \delta(\Delta P) = \Delta P_n - \Delta P_{n-1} \end{cases} \tag{7}$$

where P_{ref} is the rated power of the system and P_g is the measured generator power.

The mean wind speed υ_{wm}, which used as the third input variable, is useful to compensate the non-linear sensitivity of pitch angle to the wind speed. Table I lists the control rules for the input and output variable. In the proposed fuzzy system, nine fuzzy sets have been considered for variables: negative large (NL), negative medium large (NML), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM), positive medium large (PML), positive large (PL). At lower mean wind speed, the low sensitive of the pitch angle control means that a large reaction of pitch angle to the control variants will be needed than at higher mean wind speed. This is seen in Table I.

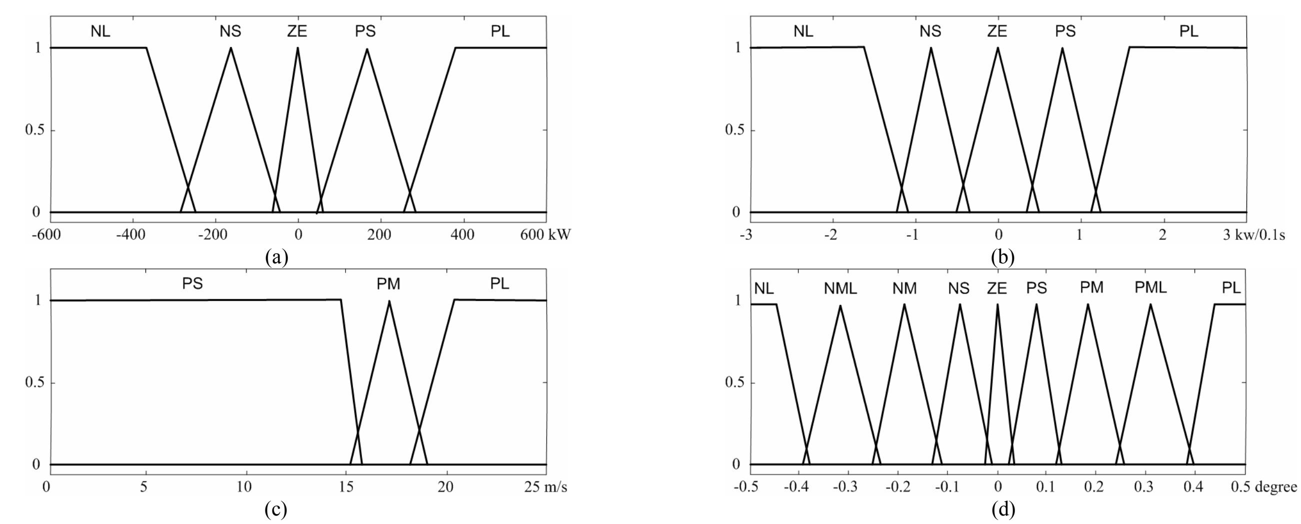


Fig. 9 Membership functions of fuzzy logic controller.(a) Input signal error of the power; (b) Input signal variation of power error; (c) Input signal wind speed; (d) Output signal variation of pitch angle.

TABLE I.
RULES OF FUZZY LOGIC CONTROLLER

υ_m	PS					PM					PL				
ΔP	NL	NS	ZE	PS	PL	NL	NS	ZE	PS	PL	NL	NS	ZE	PS	PL
δΔP															
NL	NL	NML	NM	NM	PS	NL	NM	NM	NS	PS	NML	NM	NS	NS	PS
NS	NL	NM	NS	PS	PM	NML	NM	NS	PS	PM	NML	NM	NS	ZE	PS
ZE	NML	NS	ZE	PS	PML	NM	NS	ZE	PS	PM	NM	NS	ZE	PS	PM
PS	NM	NS	PS	PM	PL	NM	NS	PS	PM	PML	NS	ZE	PS	PM	PML
PL	NS	PM	PM	PML	PL	NS	PS	PM	PM	PL	NS	PS	PS	PM	PML

An immediate and easy understanding of the controller logic can be obtained as following considerations (not consider wind speed):

1) If ΔP and $\delta(\Delta P)$ are negative large, the output power angle is too large and its amplitude is growing, consequently current pitch angle must be fast decreased.

2) If ΔP is negative large and $\delta(\Delta P)$ is positive large, the output power is higher than its reference, but since its amplitude is decreasing, pitch angle variation must be small.

3) If ΔP is small pitch angle variation must be smoothed because too large variations excite oscillatory modes.

V. SIMULATION RESULTS AND DISCUSSION

Pitch angle control systems of the wind turbine were simulated using MATLAB/SIMULINK tool to test the control strategy and evaluate the performance of the system. Table II shows the characteristics of the wind turbine system.

TABLE II.
WIND TURBINE AND GENERATOR CHARACTERISTICS

Blade radius	35 m
Hub height	82 m
Gearbox ratio	6
Generator power	1500 kW

The wind model is essential to obtain realistic simulations of the power control of the wind turbines. The model for the wind field includes turbulence as well as tower shadow effects. Fig. 10 illustrates the hub-height wind speed variation. It has a mean value of 11 m/s at the hub-height and a turbulence intensity of 30%.

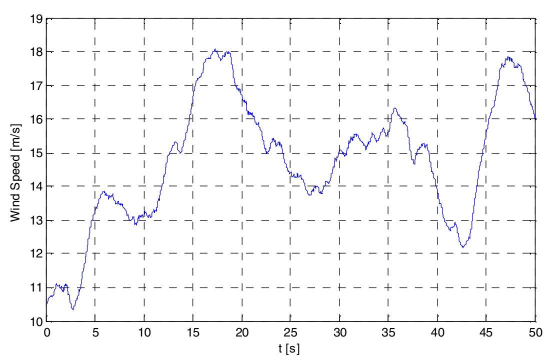


Fig. 10 Wind speeds with a mean of 11 m/s.

Fig. 11 shows the results of the conventional pitch angle control strategy where wind speed is used as the controlling variable. It is shown that if the ideal wind speed is available, the torque ripples at high wind speed, as shown in Fig. 11 from 12-40 seconds, is extremely small. This means very small fatigue loads to the wind turbine components and a long fatigue life is resulted according to the rain-flow counting method. Comparatively, one-second mean wind speed is used as the controlling variable and a deviation to the ideal performance is shown.

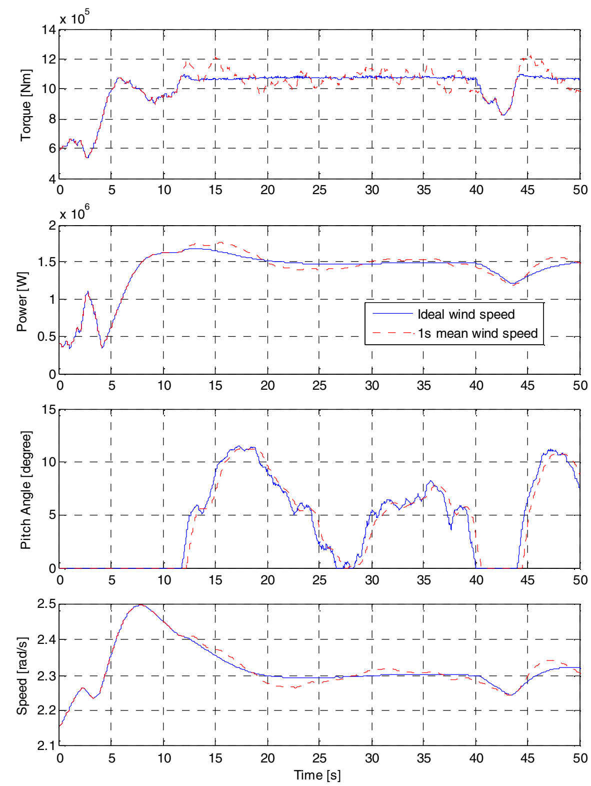


Fig. 11 Pitch angle control strategy: wind speed.

Fig. 12 shows the results of the conventional pitch angle control strategy where generator power is used as the controlling variable. The comparison of with and without gain scheduling is shown that the former has rapid pitch angle respond to the wind speed variation which is favor for minimum power and torque ripples.

The comparisons of different strategies are shown in Fig. 13. It is shown that proposed fuzzy logic control strategy have lowest torque ripples at high wind speed, which means a reduced fatigue loads to the turbine components. A narrowly lower power peak and lower torque peak is also obtained for fuzzy logic controller. However, the over-speed is not reduced by using fuzzy logic controller. The strategy using rotor speed as controlling variable has less over-speed while the torque and power ripple is most serious. From the view of smoothing the pitch angle action, the fuzzy logic control is better than other two control strategies, except the rotor speed control strategy.

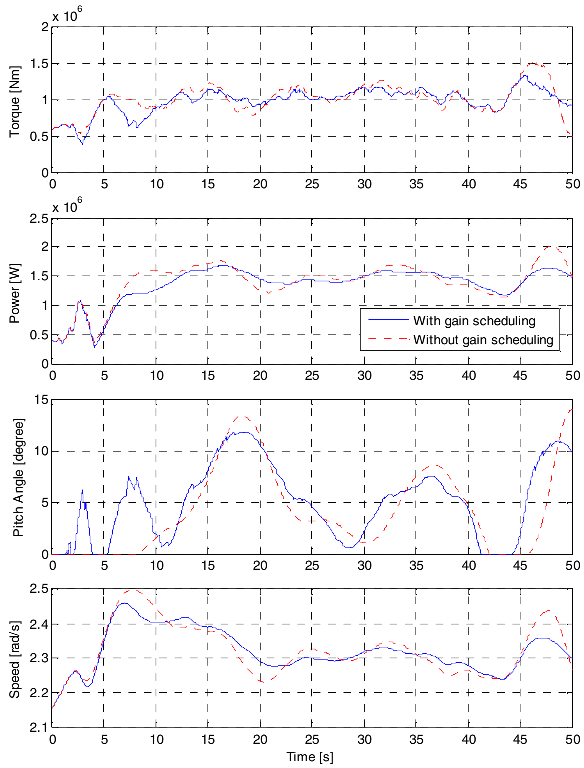


Fig. 12 Pitch angle control strategy: generator power.

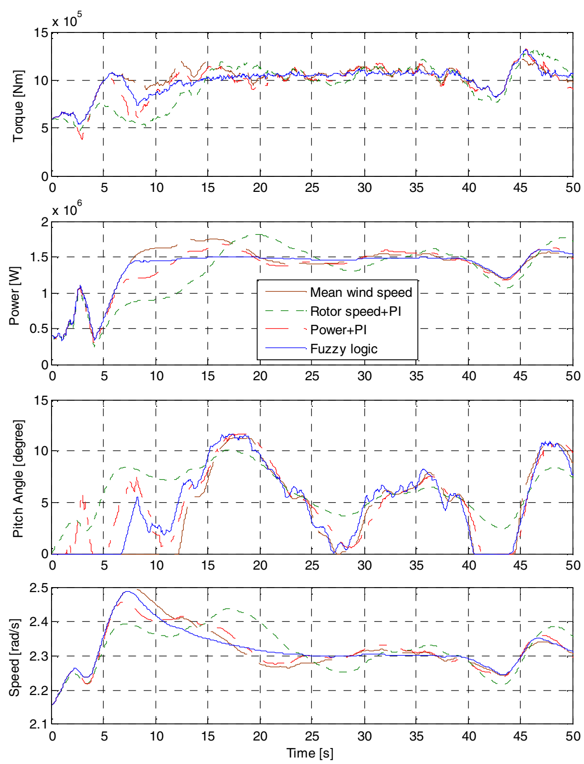


Fig. 13 Comparisons of pitch angle control strategies.

VI. Conclusion

Pitch angle control is the most common means to control the aerodynamic power generated by the wind turbine rotor. Pitch angle control also has an effect on the aerodynamic loads which may be controlled by the controller to achieve lower torque peak as well as lower fatigue loads.

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.

VII. Acknowledgment

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VIII. References

[1] T. Burton, D. Sharpe, N. Jenkins, E. Bossanyi, Wind energy handbook, *John Wiley & Sons Ltd*, Chichester, UK, 2001.

[2] DNV/Risø, Guidelines for design of wind turbines, 2nd ed., *Jydsk Centraltrykkeri*, Denmark, 2002.

[3] S. Suryanarayanan, A. Dixit, Control of large wind turbines: Review and suggested approach to multivariable design, *Proc. of the American Control Conference* 2005, Portland, USA, pp. 686-690.

[4] V. Akhmatov, Variable-speed wind turbines with doubly-fed induction generators Part I: Modelling in dynamic simulation tools, *Wind Engineering*, Vol. 26, No.2, 2002, pp. 85-108.

[5] A. D. Hansen, P. Sorensen, F. Iov, F. Blaabjerg, Control of variable speed wind turbines with doubly-fed induction generators, *Wind Engineering*, Vol. 28, No. 4, 2004, pp. 411-434.

[6] T. Senjyu, R. Sakamoto, N. Urasaki, H. Higa, K. Uezato, T. Funabashi, Output power control of wind turbine genetador by pitch angle control using minimum variance control, *Electrical Engineering in Japan,* Vol. 154, No. 2, 2006, pp. 10-18.

[7] L. Lupu, B. Boukhezzar, H. Siguerdidjane, Pitch and torque control strategy for variable speed wind turbines, *in 2006 European Wind Energy Conference Proceedings*, Athens, Greece 2006.

[8] Z. Chen, S. A. Gomez, M. McCormick, A fuzzy logic controlled power electronic system for variable speed wind energy conversion systems, *Eighth International Conference on Power Electronics and Variable Speed Drives*, Publication No. 475, 2000.

[9] A. G. Abo-Khalil, D. Lee, J. Seok, Variable speed wind power generation system based on fuzzy logia control for maximum output power tracking, *35th Annual IEEE Power Electronics Specialists Conference*, Achen, Germany, 2004.

[10] C. Jauch, T. Cronin, P. Sørensen, B. B. Jensen, A fuzzy logic pitch angle controller for power system stabilization, *Wind Energy*, 2007, pp. 19-30.

[11] S. Heier, Grid integration of wind energy conversion systems, *John Wiley & Sons Ltd*, 2nd ed., Chichester, UK, 2006.