POWER AND VELOCITY CONTROL OF WIND TURBINES BY ADAPTIVE FUZZY CONTROLLER DURING FULL LOAD OPERATION

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Abstract. Research on wind turbine technologies have focused primarily on power cost reduction. Generally, this aim has been achieved by increasing power output while maintaining the structural load at a reasonable level. However, disturbances, such as wind speed, affect the performance of wind turbines, and as a result, the use of various types of controller becomes crucial.

This paper deals with two adaptive fuzzy controllers at full load operation. The first controller uses the generated power, and the second one uses the angular velocity as feedback signals. These feedback signals act to control the load torque on the generator and blade pitch angle. Adaptive rules, derived from the fuzzy controller, are defined based on the differences between state variables of the power and angular velocity of the generator and their nominal values.

The results, which are compared with verified results of reference controller, show that the proposed adaptive fuzzy controller in full load operation has a higher efficiency than that of reference ones, insensitive to fast wind speed variation that is considered as disturbance.

1. Introduction

Nowadays, wind energy has become the most competitive forms of renewable energy. In the past decades, the size and capacity of wind turbines have been dramatically increased. Meanwhile, the structural components have been made relatively lighter to cut costs down [18]. This has put higher demands on the wind turbine control schemes and has resulted in the implementation of advanced control systems as a promising way to decrease the fatigue loads and increase the efficiency [18].

In Figure 1, a typical ideal power curve is shown in which P_a is ideal generated power and V_w is effective wind speed at rotor plane. The ideal power curve is the reference curve that the wind turbine controller should track it as close as possible. Cut-In and Cut-Out wind speeds are the lowest and the highest wind speeds for wind turbine operation, respectively and wind turbine is shut down out of this range [8].

In terms of control, the wind turbine works in two distinct regions. First region, so called the partial load operation, is between the nominal wind speed, $V_{W,N}$ (the

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wind speed at which a turbine reaches its nominal power, $P_{a,N}$) and the Cut-In wind speed. The second region, so called the full load operation, is from the nominal wind speed to Cut-Out wind speed.

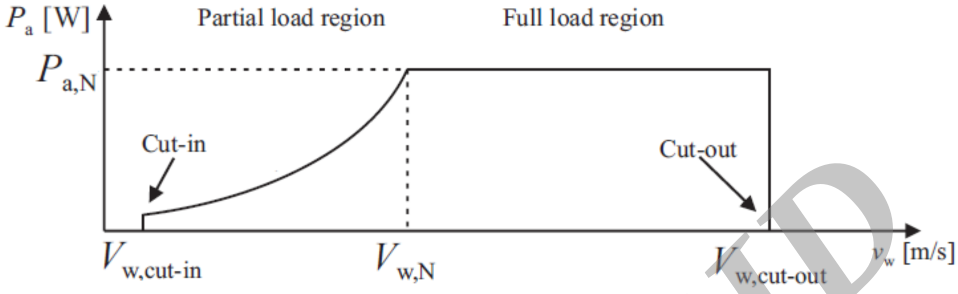

FIGURE 1. The Ideal Power Curve

In the full load operation, the available energy in wind is greater than the wind turbine nominal power, therefore, the turbine should be protected from dangerous vibrations, which damage the turbine structure and cause fatigue. In fact, keeping the turbine structure safe during the full load operation is more important than extracting maximum energy available in wind. This idea shapes the control objective in the full load region [4].

The applications of fuzzy inference system and adaptive schemes in controller design significantly have been studied recently, especially, in wind energy conversion system. Aissaoui et al [1] proposed an adaptive fuzzy PI speed controller for power regulation of wind turbine without considering the applied stress on wind turbine drive train. In similar research, Qi et al [15] used fuzzy PID control to the control of generator speed and blade pitch angle but the wind speed is used as an input for controller and the rise time is not appropriate while the steady state error is eliminated. Simani et al [17] designed adaptive controller for ideal power curve tracking on benchmark model and some good results have been reported, but the applied torsional angle of drive train, as one of control criteria, is not studied.

On the other hand, adaptive controller design using fuzzy logic, so called adaptive fuzzy controller is one of the most recent controller scheme that has attracted several researchers' attention. Elshafei et al [7] studied a new voltage regulator of a variable speed wind power generation system based on adaptive fuzzy system with nonrealistic wind speed signal. Shamshirband et al [16] analyzed wind farm by adaptive neuro fuzzy (ANFIS) optimization of the number of wind turbines net present value. Mohandes et al [14] proposed an ANFIS system to estimate effective wind speed. Although, proper estimation of wind speed is addressed, but there is some appreciable errors in wind speed estimation and it is still more rational to consider wind speed as a disturbance in control design. Bedoud et al [3] used an adaptive fuzzy gain scheduling PI controller to track the maximum power in partial load operation by control of the active and reactive power. Bououden et al [6] proposed a robust fuzzy multivariable model predictive controller (RFMMPC) using linear matrix inequalities (LMIs) formulation. Aside from suitable generator speed control, the generated power compared to nominal value and torsional stress applying on drive train are not considered.

Also, there are some other analogous works which are addressed here. Feng et al [9] controlled the pitch angle with programming of a PI fuzzy controller. Furthermore, in a similar research, Xu et al [12] studied the variable pitch wind turbine with fuzzy logic. Ata and Kocyigit [2] used an adaptive neuro fuzzy inference system model to predict the tip speed ratio and the power factor of a wind turbine. In addition, Bououden et al [5] dealt with fuzzy model based multivariable predictive control (FMMPC) for wind turbine generator. Xiyun and Xinran [19] developed a fuzzy adaptive with variable structure to increase turbine efficiency. Hou et al [11] implemented the same controller in the partial load region to maximize the extracted energy in low wind conditions. It is required to mention the main contribution of present work in comparison to the other similar works, is that the wind speed is considered as disturbance and the considerable results regardless of wind speed, are reported with proposed adaptive fuzzy controller while there is no significant change in applied torsional angle of drive train.

The rest of this paper is organized as follows. In section 2, wind turbine model is described. The control strategies in full load operation is outlined in section 3. The reference and adaptive fuzzy controllers are considered and simulated in sections 4 and 5, respectively. The simulation results are illustrated in section 6, accordingly, the outcomes are concluded in section 7.

2. **Wind Turbine Model**

In this section a nonlinear model of a 4.8MW wind turbine is described. This model is used for the proposed control algorithms [8, 4]. The wind turbine parameters can be found in Appendix.

2.1. **Aerodynamic Model.**

The rotor of the wind turbine transfers energy from the wind to the rotor shaft that is rotating at the speed $\omega_r(t)$. The power from the wind depends on the wind speed, V_r, the air density, ρ, the swept area by blades, A and power coefficient, $C_P(\lambda(t), \beta(t))$. The power coefficient depends on the pitch angle of the blades, $\beta(t)$, and the ratio between the speed of the blade tip and the wind speed (tip-speed ratio) denoted as $\lambda(t)$ [4]. The generated aerodynamic torque is shown in (1).

$$\begin{aligned} &T_a(t) = \tfrac{1}{2\omega_r(t)}\rho A V_r^3 C_P(\lambda(t), \beta(t)) \qquad [Nm] \\ &\lambda = \tfrac{\omega_r.R}{V_r} \end{aligned} \tag{1}$$

where R is blade length and $T_a(t)$ is aerodynamic torque applying on the rotor. The coefficient C_p describes the aerodynamic efficiency of the rotor by a nonlinear mapping. An empirical formula for power coefficient is shown in (2) [10]:

$$\begin{aligned} &C_P(\lambda, \beta) = C_1(\tfrac{C_2}{\lambda_i} - C_3\beta - C_4)e^{\frac{-C_5}{\lambda_i}} + C_6\lambda \\ &\tfrac{1}{\lambda_i} = \tfrac{1}{\lambda+0.08\beta} - \tfrac{0.035}{\beta^3+1} \end{aligned} \tag{2}$$

In (2), the constant coefficients are $C_1 = 0.5176$, $C_2 = 116$, $C_3 = 0.4$, $C_4 = 5$, $C_5 = 21$ and $C_6 = 0.0068$. The power coefficient surface is shown in Figure 2. It should be noted that the maximum of C_p is 0.48 and occurs at $\beta = 0°$ and $\lambda = 8.1$.

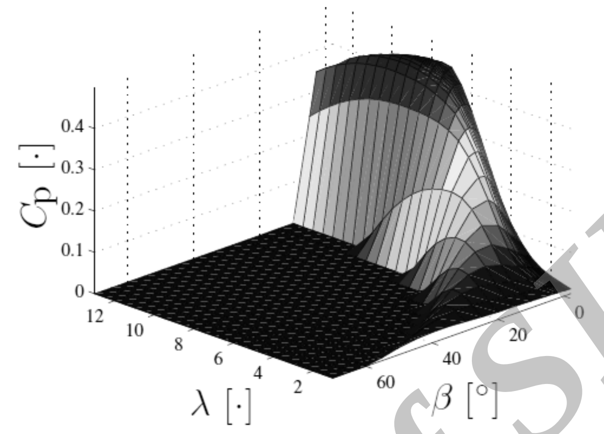

FIGURE 2. The Surface of Empirical Equation for Power Coefficient

2.2. **Drive Train Model.** The drive train model consists of a low-speed and a high-speed shafts that their inertia are J_r andJ_g , respectively. The shafts are interconnected by a gear box that its gear ratio is N_g, combined with torsion stiffness, K_{dt} and torsion damping, B_{dt} which result in a torsion angle θ_Δ. The drive train efficiency is η_{dt}. B_r and B_g are viscous frictions rotor and generator shafts, respectively. On the other hand, the load torque applied on the generator by grid is $T_g(t)$ and the generator speed is denoted by $\omega_g(t)$. The linear model of drive train is given as below [4]:

$$J_r\dot{\omega}_r(t) = T_a(t) - K_{dt}\theta_\Delta(t) - (B_r + B_{dt})\omega_r(t) + \tfrac{B_{dt}}{N_g}\omega_g(t) \tag{3}$$

$$J_g\dot{\omega}_g(t) = \tfrac{\eta_{dt}K_{dt}}{N_g}\theta_\Delta(t) + \tfrac{\eta_{dt}B_{dt}}{N_g}\omega_r(t) - (B_g + \tfrac{\eta_{dt}B_{dt}}{N_g^2})\omega_g(t) - T_g(t) \tag{4}$$

$$\dot{\theta}_\Delta(t) = \omega_r(t) - \tfrac{1}{N_g}\omega_g(t) \tag{5}$$

2.3. **Pitch System Model.** The pitch system should track a reference value of pitch angle, β_{ref} and is modeled as a first order system. This model consists of time constant, τ and communication delay, t_d [4].

$$\dot{\beta}(t) = -\frac{1}{\tau}\beta(t) + \frac{1}{\tau}\beta_{ref}(t - t_d) \tag{6}$$

Indeed, β_{ref} is determined by controller to achieve the control objectives.

2.4. **Generator and Converter Models.** Electric power is produced by the generator, while a power converter is used to identify the generator output with the utility grid frequency and to control the current in the generator. The generator torque, (7), is adjusted by the reference $T_{g,ref}$. The dynamics of the converter is approximated by a first order system with time constant τ_g and communication delay $t_{g,d}$.

$$\dot{T}_g(t) = -\frac{1}{\tau_g}T_g(t) + \frac{1}{\tau_g}T_{g,ref}(t - t_{g,d}) \tag{7}$$

The power produced by the generator can be approximated by (8), where η_g denotes the efficiency of the generator.

$$P_g(t) = \eta_g \omega_g(t) T_g(t) \tag{8}$$

2.5. **Assembled Model.** In terms of control theory, all aforementioned subsystems can be connected as Figure 3. It is obvious that $T_{g,ref}$ and β_{ref} are two control variables. It should be noticed that available measurements are generator torque, pitch angle, generator speed, and rotor speed. On the other hand, the output power is determined as the product of the measured values of speed and torque of the generator, as described in (8). Generator torque and pitch angle actuators have some practical limitations as below:

$$T_{g,\min} < T_g < T_{g,\max} \; and \; \dot{T}_{g,\min} < \dot{T}_g < \dot{T}_{g,\max}$$
$$\beta_{\min} < \beta < \beta_{\max} \; and \; \dot{\beta}_{\min} < \dot{\beta} < \dot{\beta}_{\max}$$

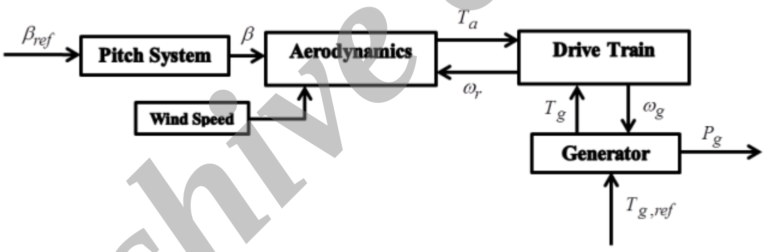

FIGURE 3. Block Diagram of the Wind Turbine Model

3. Control Strategy

The main objective of controller, in full load operation, is tracking the ideal power curve as close as possible. Although the available wind power in full load region is higher than the wind turbine nominal value, but in order to avoid undesirable and unsafe operating conditions and keep the overall stress in reasonable level, wind turbine should only produce its nominal power. Accordingly, the optimized operation in the full load region is denoted as constant power generation.

The basic control strategy is retaining generator torque at nominal value and controlling angular velocity with pitching the blades to produce nominal power [13].

Additionally, steady state error should be eliminated in generated power, accordingly, the best controller scheme is to control power and velocity, simultaneously, with regulating the torque of the generator and the blade pitch angle, respectively [8].

On the other hand, in industrial wind turbines, it is not possible to measure the wind speed accurately and it is reasonable to consider wind speed as disturbance [14]. Indeed, with this proposed controller, there is no need for accurate measurement of wind speed and controller is more practical for industrial wind turbines.

In this research, pitch angle (velocity control unit) and generator torque (power control unit) are adjusted based on the angular velocity of the generator and generated power, respectively.

4. Reference Controller

Reference controller, as illustrated in Figure 4, is a PI controller [13]. Indeed, the reference controller outputs are used to evaluate the proposed adaptive fuzzy controller. In this controller, the generator reference torque, $T_{g,ref}$, is set at nominal value and the reference pitch angle, β_{ref}, is regulated with PI controller. The difference between generator angular velocity, ω_g and the nominal value, $\omega_{g,N}$, is used as feedback signal to PI controller.

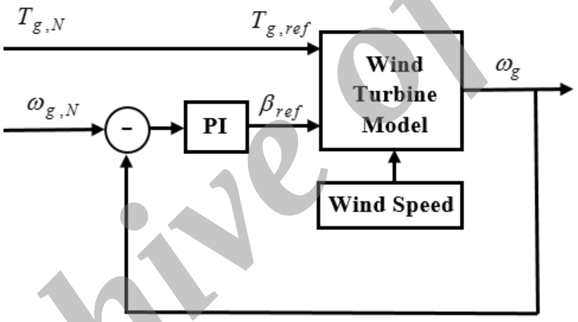

Figure 4. Reference Controller

5. Adaptive Fuzzy Controller

The overall schematic plan for proposed adaptive fuzzy controller is shown in Figure 5. In this research, to increase controller performance regardless of wind speed variation, the direct fuzzy adaptive controller is used. As it is mentioned in previous section, both torque and pitch angle control signals are active and therefore, there are two independent fuzzy adaptive control units.

Adaptive rules which are applied on the centers of output membership functions, are defined as below:

$$\frac{d\bar{\theta}}{dt} = \gamma s \xi(\bar{x}) \tag{9}$$

where $\bar{\theta}$ is the centers of output membership functions vector, γ is learning rate and s is slide surface. x and ξ are state variables vector and fuzzy principal function, respectively.

$$\bar{\theta} = [c^1, ..., c^T] \tag{10}$$

$$s = \bar{k}^T \bar{e} \tag{11}$$

where $\bar{k}$ is hyper slide surface coefficients vector and $\bar{e}$ is the errors between state variables and reference variables.

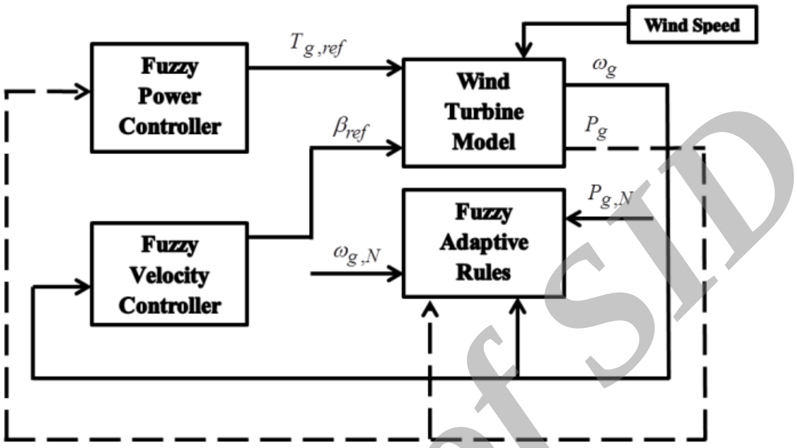

FIGURE 5. Fuzzy Adaptive Controller Structure

Fuzzy control signal, u_c, can be defined as below:

$$u_c(\bar{x}|\bar{\theta}) = \bar{\theta}^T \xi(\bar{x}) \tag{12}$$

$$\xi = \frac{\prod_{l=1}^{n} \mu_{fil}(x_i)}{\sum_{l=1}^{m} (\prod_{l=1}^{n} \mu_{fil}(x_i))} : \, fuzzy\, basis\, function\, (FBF) \tag{13}$$

m, n andμ_{fil}, are rules number, state variables number and Gaussian membership function, respectively. The fuzzy inference engine is product; including, algebraic t-norm, singleton fuzzifier and the centers of mean defuzzifier.

Initial value is selected as $\bar{\theta}\,(t = 0) = 0$. State variables, which act as turbine outputs and the inputs of adaptive fuzzy controllers, are generated power, generator angular velocity, and their derivatives with respect to corresponding controllers. It should be noted that to avoid computational errors during simulation all of them have been normalized. Membership functions for both controllers are shown in Figures 6 and 7.

Slide surfaces for power and velocity controller are defined as:

$$\begin{aligned} s_T &= -0.399 e_P - 0.001 \dot{e}_P \\ s_\beta &= 8 e_{\omega_g} + 2 \dot{e}_{\omega_g} \end{aligned} \tag{14}$$

where $e_P$and $\dot{e}_P$ are power error state variable and its derivative, $e_{\omega_g}$and $\dot{e}_{\omega_g}$are generator angular velocity error state variable and its derivative, respectively.

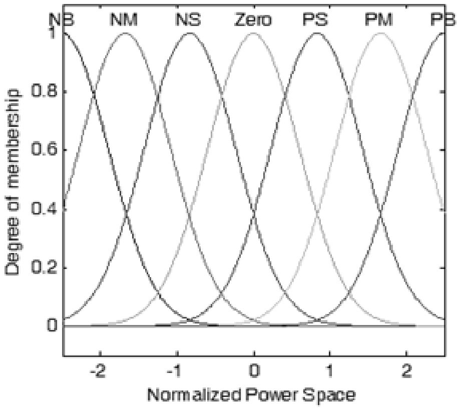

Figure 6. Membership Functions of Normalized Power

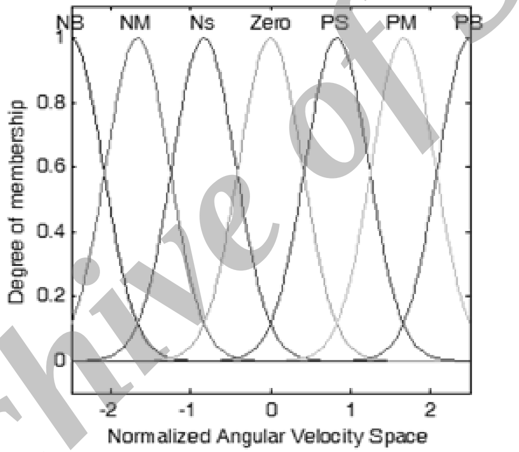

Figure 7. Membership Functions of Normalized Angular Velocity

With respect to number of membership functions, 49 rules are defined. Learning rate for angular velocity and power adaptive controllers rules are $\gamma_{\omega_g} = 1$ and$\gamma_P = 6$, respectively. As discussed earlier, controller strategy is to keep power and angular velocity at their nominal values; therefore references for their derivatives are zero.

6. **Simulation Results**

The wind turbine model and controller are simulated in MATLAB/Simulink software. In Figure 8 the wind speed signal is shown.

Wind turbine nominal power and nominal generator speed are 4.8 MW and 162.45 rad/sec, respectively [4].

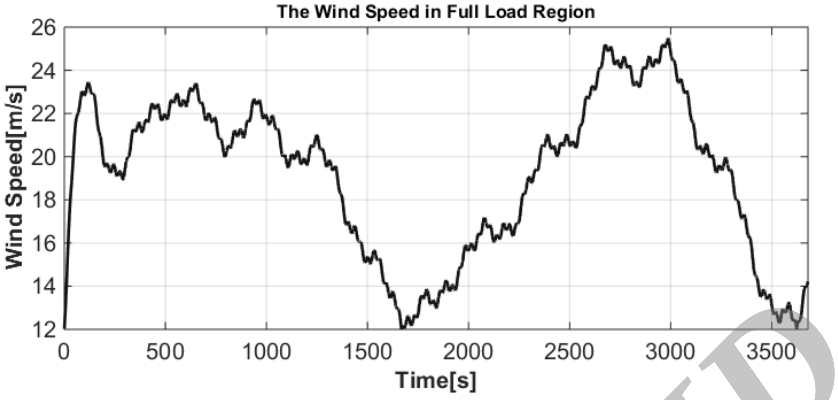

FIGURE 8. Wind Speed

The evaluation of results is performed by comparison between responses of adaptive fuzzy controller and reference controller [15].

The main advantage of adaptive fuzzy controller is in the low wind speed range in which the controller reduces error by adapting its centers of membership functions.

One of the control objective in full load region is keeping the generated power at nominal value. Figure 9 shows the simulation results for generated power. The improved operation of adaptive fuzzy controller compared with those of reference PI is evident. The overshoot at the beginning is decreased about 1%. On the other hand, the steady state error with respect to nominal values is completely eliminated. Indeed, by using adaptive fuzzy controller, the output power is kept at nominal value obviously while correspond values for PI controller vary around the nominal value regarding the wind speed variation. Especially, noteworthy steady state error and overshoot are obvious whenever the wind speed is approximately constant and varies fast, respectively. It should be noted that rise time is slightly improved via fuzzy adaptive controller.

In addition to generated power, angular velocity of generator should be kept at nominal value to avoid unsafe operation of wind turbine. The comparison of angular velocity of generator for adaptive fuzzy controller and reference controller is shown in Figure 10. The reduction in overshoot of angular velocity curve is obvious. On the other hand the steady state error in angular velocity is decreased.

It should be noted that improvement in the generated power compared to angular velocity is remarkable and this is because of higher learning rate of power adaptive controllers. In fact, the main control objective is producing nominal power and the angular velocity only should be kept in reasonable range of its nominal value. The angular velocity can be improved be increasing its learning rate of fuzzy controller, but consequently, the controller shows a more aggressive behavior and increases the total induced torsional load on drive train. The torsional angle of drive train can be considered as a numerical measurement of induced stress on wind turbine that affects on efficiency and maintenance cost of wind turbine. Therefore the induced torsional angle on drive train of wind turbine should be considered for proposed

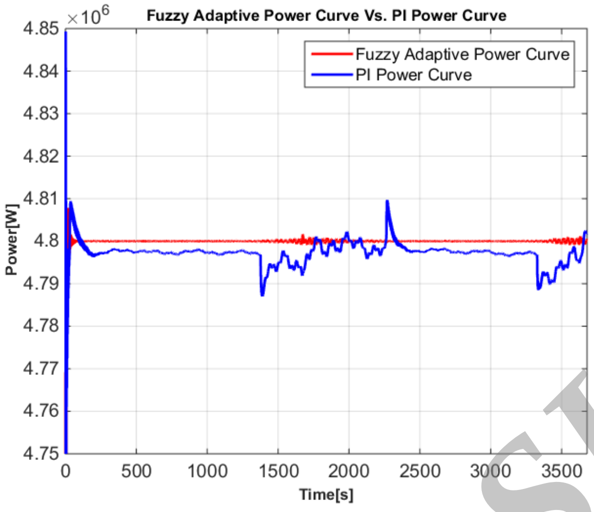

FIGURE 9. Generated Power Comparison Between Fuzzy Adaptive Controller and PI Controller

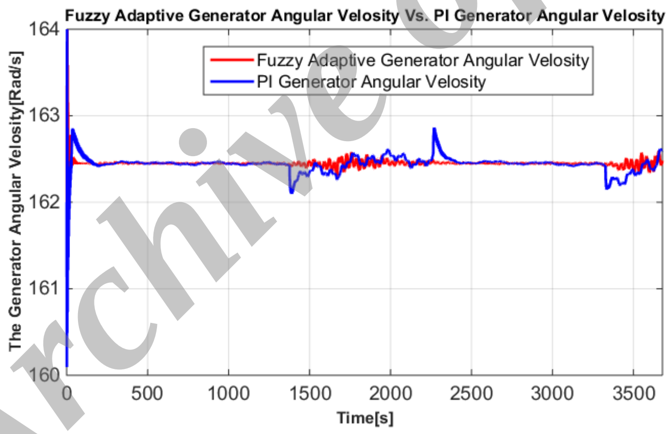

FIGURE 10. Generator Angular Velocity Comparison Between Fuzzy Adaptive Controller and PI Controller

fuzzy adaptive controller. The total torsion angle is shown in Figures 11 and 12 for both fuzzy adaptive and reference controllers.

It is obvious that the torsion angle has been reached to constant value with adaptive fuzzy controller after 130 seconds, while it has taken 400 seconds with reference controller. Additionally, the significant variations in torsion angle due to fast variation of wind speed, are decreased considerably.

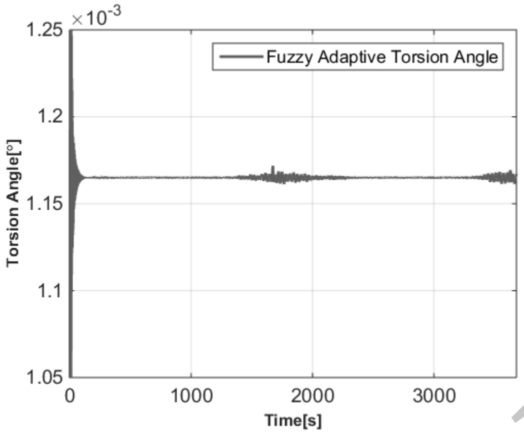

Figure 11. Torsional Angle of Drive Train for Adaptive Fuzzy Controller

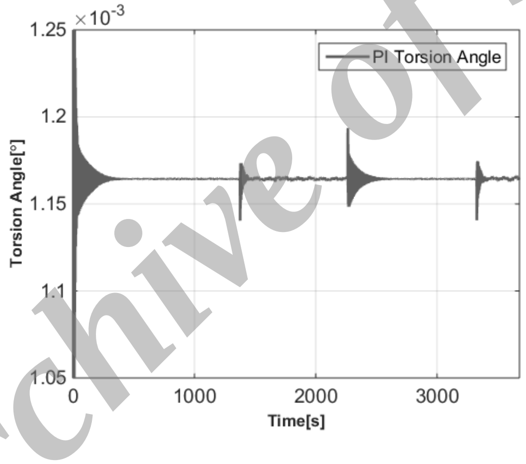

Figure 12. Torsional Angle of Drive Train for Reference Controller Controller

7. Conclusion

In the present research, the performance of wind turbine is improved by the use of an adaptive fuzzy controller in the full load region. The control strategy in the full load operation is to maintain the generated power at the nominal value to avoid excessive vibration whilst the generator angular velocity should not vary considerably from nominal value to keep the induced torsional angle and stress in reasonable level. The adaptive fuzzy controller is employed to improve the performance of the controller with respect to the fast variation of wind speed, as a disturbance.

In addition to the generator angular velocity control, the power control has also been performed by torque controller to eliminate steady state error. Therefore, the controller consists of two velocity and power controller units. The performance of the controller was evaluated by comparing its responses to the reference controller ones. The comparison shows that the overshoot and steady state error significantly are reduced due to adaptive fuzzy controller during varying wind speed. Consequently, results illustrate that with the proposed controller, wind turbine can produce its nominal power insensitive to the wind speed variation.

Also, it is obvious that variation of the drive train torsional angle, as a measurement of induced stress, is reduced. Accordingly, with proposed controller, the maintenance cost of wind turbine will be lower. It should be noted that wind turbine control system is still an open field and some interesting issues, such as adaptive fuzzy fault tolerant control of wind turbines, can be conducted, as future work of current research.

8. **Appendix**

Tables 1-4 show the value of parameters used in wind turbine modeling [18].

Parameter	Swept Area (A)	Air Density (ρ)	Blade Length (R)
Value	10387 [m^2]	1.225 [kg/m^3]	57.5 [m]

TABLE 1. Aerodynamic

Parameter	Value
Time Constant of The First Order System (τ_g)	20 [ms]
Communication Delay of The Converter ($t_{g,d}$)	10 [ms]
Minimum Change Rate of Generator Torque ($\dot{T}_{g,\min}$)	-50 [MNm/s]
Maximum Change Rate of Generator Torque ($\dot{T}_{g,\max}$)	50 [MNm/s]
Minimum Generator Torque ($T_{g,\min}$)	0 [Nm]
Maximum Generator Torque ($T_{g,\max}$)	3500 [Nm]
Minimum Generator Power ($P_{g,\min}$)	0 [W]
Maximum Generator Power ($P_{g,\max}$)	5.3 [MW]

TABLE 2. Generator and Converter

Parameter	Value
Time Constant of The First Order System ($\tau.$)	50 [ms]
Communication Delay of The Pitch Actuator ($t_{g,d}$)	10 [ms]
Minimum Change Rate of Pitch Angle ($\dot{\beta}_{\min}$)	-10 [$^\circ/s$]
Maximum Change Rate of Pitch Angle ($\dot{\beta}_{\max}$)	10 [$^\circ/s$]
Minimum Pitch Angle ($\beta_{\min}$)	-10 [$^\circ$]
Maximum Pitch Angle ($\beta_{\max}$)	40 [$^\circ$]

TABLE 3. Pitch Actuator

Parameter	Value
Torsion Damp Coefficient Of The Drive Train (B_{dt})	9.45 $[MNm/(rad/s)]$
Viscous Friction Of The High Speed Shaft (B_g)	3.034 $[Nm/(rad/s)]$
Viscous Friction Of The Low Speed Shaft (B_r)	27.8 $[KNm/(rad/s)]$
Moment Of Inertia Of The High Speed Shaft (J_g)	390 $[kgm^2]$
Moment Of Inertia Of The Low Speed Shaft (J_r)	55 $[Mkgm^2]$
Torsion Stiffness Of The Drive Train (K_{dt})	2.7 $[GNm/rad]$
Drive Train Gear Ratio (N_g)	95
Efficiency Of The Drive Train (η_{dt})	0.97

TABLE 4. Drive Train

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POWER AND VELOCITY CONTROL OF WIND TURBINES BY ADAPTIVE FUZZY CONTROLLER DURING FULL LOAD OPERATION

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کنترل توان و سرعت توربین بادی با استفاده از کنترل‌کننده فازی – تطابیقی در ناحیه عملکردی بار کامل

چکیده. پژوهش های انجام شده در زمینه تکنولوژی توربین‌های بادی، در درجه اول به بررسی کاهش هزینه انرژی می‌پردازند.به طور کلی این هدف با افزایش توان تولیدی همراه با ثابت نگه داشتن بار سازه‌ای وارد شده بر روی توربین بادی در یک محدوده‌ی معتدل قابل دست‌یابی می‌باشد. به هر حال اغتشاشاتی نظیر باد عملکرد توربین بادی را تحت تاثیر قرار می‌دهند که به همین سبب استفاده از انواع مختلف کنترل‌کننده بسیار مهم می‌باشد.

در این مقاله به بررسی دو کنترل‌کننده فازی تطبیقی روی توربین بادی در ناحیه عملکردی بار کامل پرداخته شده است.این دو کنترل‌کننده به‌ترتیب توان تولیدی و سرعت زاویه‌ای ژنراتور را به عنوان سیگنال های بازخورد استفاده می‌کنند. با به کار بردن این دو سیگنال بازخورد برای کنترل گشتاور بار و زاویه گام پره‌های توربین بادی مورد استفاده قرار می‌گیرند. قوانین تطبیقی که از کنترل‌کننده فازی استخراج می‌شوند، بر اساس تفاوت متغیرهای حالت توان و سرعت زاویه ژنراتور و مقادر نامی آن‌ها، تعریف می‌شوند.نتایج کنترل‌کننده پیشنهادی با مقایسه با نتایج کنترل‌کننده مرجع، نشان‌دهنده‌ی بازدهی بالای کنترل‌کننده فازی – تطبیقی نسبت کنترل‌کننده مرجع می‌باشد.لازم به ذکر است که کنترل‌کننده پیشنهادی به سرعت بار که به صورت اغتشاش در نظر گرفته شده است، غیر حساس می‌باشد.