Design of an Integral Fuzzy Logic Controller for a Variable-Speed Wind Turbine Model

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***Abstract*—The demand for electricity is continuously growing around the world and thus the need for renewable and long-lasting sources of energy has become an essential challenge. Wind turbines are considered one of the major sources of renewable electricity generation. Therefore, there is a crucial demand for wind turbine model and control systems that are capable of precisely simulating the actual wind power systems. In this paper, an advanced fuzzy logic controller is proposed to control the speed of a wind turbine system. Initially, aero dynamical, mechanical and electrical models of two mass wind turbines models are derived. Analytical calculation of the power coefficient is adopted through a nonlinear function of six coefficients that mainly depends on pitch angle and tip speed ratio. The ultimate power output from the turbine can reach up to 50 % which is achieved at zero pitch angle with an approximately tip speed ratio of eight. This is then followed by designing a hybrid fuzzy-plus I pitch controller to regulate the speed of the wind turbine shaft. In general, fuzzy logic control strategy have the advantages over traditional control techniques especially when the system is highly non-linear and has to deal with strong disturbances such as wind turbulence. To evaluate the reliability and robustness of the controller, the response of the wind turbine system is tested under several types of disturbances including wind fluctuation, sudden disturbances on high and low speed shafts. Simulation findings reveals that the performance of fuzzy-integral control technique outweighs that of conventional fuzzy approach in terms of multiple performance evaluation indexes such as zero overshoot and steady state error, rise time and a settling time of (32.9 s) (44.7 s) respectively. The reliability and robustness of the controller is tested by applying speed and torque disturbances of 25% of their maximum ranges. Results have revealed that the controller was able to reject all disturbances efficiently with a change in pitch angle up to a maximum of 10 degrees in order to retain a constant rotor speed at 1000 rpm.**

Keywords—Renewable Energy; Wind Turbine; Aerodynamic Modeling; Fuzzy Logic; Speed Control.

I. INTRODUCTION

The exponential growth in electricity demand due to factors such as population growth, urbanization, and technological advancements poses a significant challenge for humanity. However, the urgent need to address climate change and the diminishing reserves of fossil fuels has placed great importance on shifting towards renewable energy sources [1]-[6]. Among the various forms of clean energy, wind power has gained substantial popularity. Wind turbine installations offer a sustainable means of generating electricity by harnessing the power of wind and converting it into electrical energy [7]-[9]. Over the past decades, the topics of wind turbine control and dynamic model's simulations have become increasingly popular and drawn great attention [10]-[18].

The research interest in wind turbine application mainly concentrated on how to limit wind turbine loading, reduce speed fluctuation of the generator and converter, and ensure a maximum output power. From this point of view, the rotor speed of the wind turbine must be controlled effectively. There are variety of challenges when dealing with wind turbine control such variable wind conditions, changing loads, torque disturbances, main grid integration, and obtaining an optimal rotor speed to capture maximum energy. In this work, integral fuzzy is implemented on a complete wind turbine model having wind fluctuation and torque disturbance.

Initially, classical control techniques such as PID (Proportional-Integral-Derivative) has been implemented to directly control the pitch angle of the blade in order to limit both speed and power of the turbine as discussed in [19]-[23] whereas the gains K_p, K_i, and K_d are tuned to optimize the controller's performance for the system. These types of controllers require the wind turbine model to be linearized. Thus, this method's major drawback is that when the operating points are altered, the control performance deteriorates [24]-[26]. PID controller has been implemented widely mainly for its simplicity, However fractional order PID ,which is a variant of the traditional PID controller that allows for fractional orders in its integral, and derivative components, is preferred over typical PID controller for two – mass wind turbine system [27]. This is mainly because of its improved control performance, increasing robustness since additional kinds of tuning elements which provides another degree freedom to tune the controller response, better adaptability and reducing overshoots [28], [29].

The regulation of the rotor speed of the turbine is not easy task to perform and need more sophisticated control schemes. One of the solutions to tackle this issue is to design variable speed Wind Turbine Generator (WTG) which is used to control the power captured over a range of wind speeds [30]. Also, wind turbine pitch angle control has been implemented using the linear quadratic Gaussian (LQG) approach. The LQG controller is widely recognized for its reliability when it comes to both phase and gain margins. However, this controller's performance is again constrained by the wind turbines' strong nonlinearities [31], [32]. A different approach utilizing a sliding-mode control system has been adopted for pitch angle regulation, which offers strong immunity to parametric uncertainties of the wind turbine. However, this approach is reliant on the wind turbines' mathematical model [33].

The integration of fuzzy logic controllers within variable-speed wind turbines has been shown to yield superior power generation performance and enhanced efficiency. The significance of employing fuzzy controllers resides in their capacity for dealing with nonlinearity, reject disturbances and augmenting system stability. A comparative study was performed by [34] between two classical control strategies of fuzzy logic controllers applied to the same variable speed wind turbine plant. Other researcher applied an enhanced fuzzy PI controller, where the gains (KP, Ki) are computed via Fuzzy Logic [35]-[39]. The outcomes obtained are improvement of torque control loop, steady state and dynamic responses and performance under severe conditions of operation. For limiting the turbine output power and the speed of the generator , a new pitch angle control approach based on fuzzy logic control is proposed [40] at which the generator output power and speed are used for the fuzzy inputs instead of the wind speed. The results showed that the wind turbine's output power and speed are kept at their rated values without any ripples. The main contribution of this research aims to demonstrate that the integral fuzzy controller is significantly superior to the conventional fuzzy controller in regulating the rotor speed of the wind turbine while taking into account the effects of both wind fluctuation and torque disturbances.

II. Wind Turbine Dynamic Modelling

The entire wind turbine dynamic model comprises three sections of aerodynamical, mechanical and electrical modelling. First, the aerodynamical modeling that involves converting the wind kinetic energy captured by the blades into a mechanical energy at the turbine's rotor. The obtained power from the wind turbine depends on the wind speed (V), size of the rotor (R), air density (ρ) and the power coefficient (C_p) which varies according to the pitch angle of the blades (β) and the tip speed ratio (λ) [41]-[44].

In aerodynamic modeling, the relationship between the output power generated from the wind turbine and the input wind speed can be expressed as:

$$P = \frac{1}{2}\pi R^2 \rho V^3 C_p(\beta, \lambda) \tag{1}$$

There are several possible approaches for calculating the power coefficient (C_p) of a wind turbine. This includes analytical approximation, lookup table approach and blade element method [45], [46]. In analytical calculation, the power coefficient (C_p) is expressed in eq. 2 by a nonlinear function of six coefficients that depends on (β and λ)

$$C_p(\beta, \lambda) = C_1\left(\frac{C_2}{\lambda_l} - \beta.C_3 - C_4\right)e^{\frac{-C5}{\lambda_l}} + \lambda.C_6 \tag{2}$$

The coefficients C_1 to C_6 and λ_l are given in Table I. The relationship between the coefficient of performance (C_p) and tip speed ration (λ) of a variable wind speed for different pitch angle of the turbine's blade is shown in Fig. 1. It can be concluded that the maximum power output from the turbine can be obtained at zero pitch angle with tip speed ratio of approximately eight.

TABLE I. Power Coefficients [45][46]

Coefficient	Value	Coefficient	Value
C_1	0.5176	C_5	21
C_2	116	C_6	0.0068
C_3	0.4	λ_l	$(\frac{1}{\lambda + 0.008\beta} - \frac{0.035}{\beta^3 + 1})^{-1}$
C_4	5		

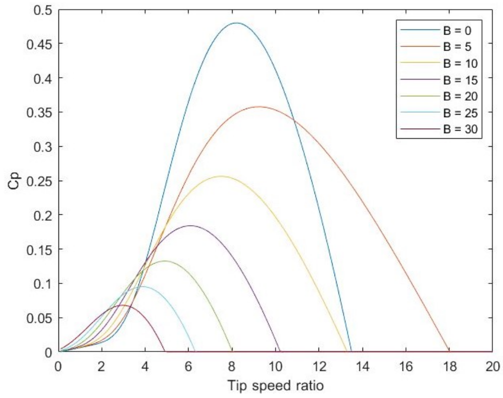

Fig. 1. Tip speed vs. coefficient of performance curve

The complete aerodynamically model of the wind turbine implemented in MATLAB Simulink is shown in Fig. 2.

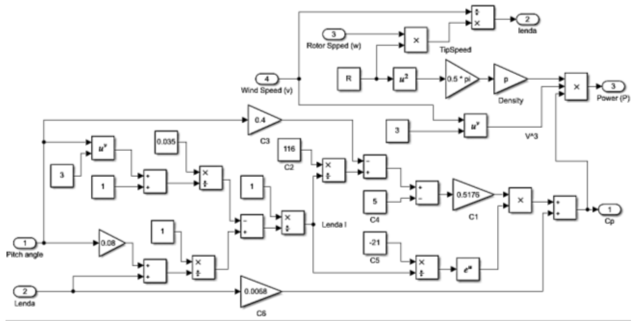

Fig. 2. Aero-dynamical model

The dynamic modelling of the wind turbine mechanical drive train is usually expressed as a two-mass model system because it is consisted of two inertias. The low-speed shaft's inertia is primarily generated from the blades and the hub of the wind turbine while the inertia of high-speed shaft is mainly produced by the generator. The damping and stiffness of both shafts are merged in one equivalent damping and stiffness located before the gearbox at the low-speed side [47]-[49]. The two-mass mechanical drive train of wind turbine model is shown in Fig. 3. The characteristic equation of wind turbine model is derived as follow:

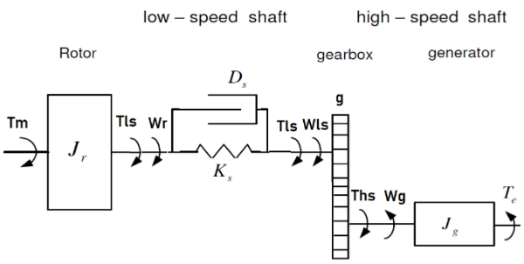

Fig. 3. Two-mass mechanical drive train model

In Mechanical Modelling, the mechanical torque initially obtained from the aerodynamical model can be calculated from dividing the power over the rotor speed.

$$T_m = \frac{p}{W_r} = \frac{\frac{1}{2}\pi R^2 \rho V^3 C_p(\beta, \lambda)}{W_r} \tag{3}$$

The change in the angular speed of the rotor $\dot{W_r}$ is caused by the difference between the mechanical torque T_m and the torque of the low-speed shaft's T_{ls}

$$T_m - T_{ls} = J_r \dot{W_r} \tag{4}$$

The torque of the low-speed shaft's T_{ls} can be expressed in eq. (5) to (7) where K_s and D_s are the combined shafts stiffness and damping respectively.

$$T_{ls} = K_s . \Delta\theta + D_s . \dot{\Delta\theta} \tag{5}$$

$$T_{ls} = K_s . \frac{1}{s}(W_r - W_{ls}) + D_s . (W_r - W_{ls}) \tag{6}$$

$$T_{ls} = K_s . \frac{1}{s}\left(W_r - \frac{W_g}{g}\right) + D_s . \left(W_r - \frac{W_g}{g}\right) \tag{7}$$

The torque of the high-speed shaft's T_{hs} drives the inertia of the generator and it is opposite by the electromagnetic torque T_e.

$$T_{hs} - T_e = J_g \dot{W_g} \tag{8}$$

$$\frac{T_{ls}}{g} - T_e = J_g \dot{W_g} \tag{9}$$

The opposing electromagnetic torque is given in equation (10) where K_1 and K_2 are the electromagnetic torque coefficients [49].

$$T_e = K_1 W_g^2 - K_2 W_g \tag{10}$$

The complete mechanical drivetrain model of the wind turbine implemented in MATLAB Simulink is shown in Fig. 4.

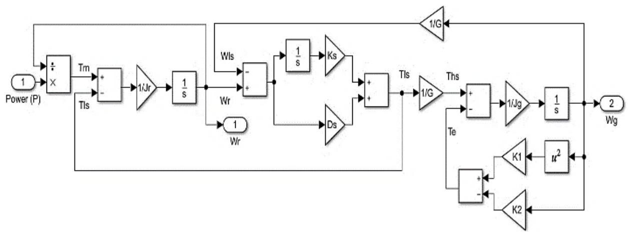

Fig. 4. MATLAB drive train model

The main parameters of the wind turbine system utilized for in the simulation are listed in Table II.

TABLE II. WIND TURBINE SYSTEM'S PARAMETERS

Parameter	Value
Radius of the turbine	21.65 m
Gear ratio	43.165
Inertia of the turbine	3.25e5 kg.m^2
Inertia of the generator	34.4 kg.m^2
Stiffness coefficient of the shaft	2.691e5 Nm/rad
Damping coefficient of the shaft	9500 Nm/rad

III. FUZZY LOGIC CONTROL DESIGN

Fuzzy logic controller has been utilized for regulating the speed of the wind turbine rotor through the adjustment of pitch angle. The main reason behind using fuzzy logic controller instead of classical control technique is that the current wind turbine system is considered highly nonlinear and hence requires a control approach that can deal well with such nonlinearity. In addition, fuzzy logic controller eliminates the need for any linearization procedure [50]-[53]. However, traditional control method, such as PID controller, will not be able to work without linearizing the system around some operating points. On the other hand, the main challenge of designing fuzzy controller is the absence of systematic methodology to select the membership function for the inputs and outputs and hence it mostly relies on human experience. The other key challenge during the design of the fuzzy logic controller is selecting optimum gain values of the controller. The design of the fuzzy controller comprises three main sections: fuzzification, interferential mechanism and defuzzification [54], [55].

The linguistic rule base of the designed fuzzy logic controller has been represented as a matrix shown in Table III. The first column represents the error (E) while the first row represents the change in error (EC). The linguistic symbols of the control action (pitch angle) are denoted as follow: negative big (NB), negative small (NS), zero (Z), and positive small (PS) and positive big (PB).

TABLE III. RULES OF THE FUZZY LOGIC CONTROLLER

E/CE	NB	NS	Z	PS	PB
NB	PB	PB	PB	PZ	Z
NS	PB	PS	PS	Z	NS
Z	PB	PS	Z	NS	NB
PS	PS	Z	NS	NB	NB
PB	Z	NS	NB	NB	NB

After generating the fuzzy input, fuzzy inference is performed to calculate the fuzzy profile of the output taking into account the effect of each rule included in the rule base. Finally, the fuzzy output will be converted to a crisp control signal in a process called defuzzification. The Membership functions of speed error signal, variation of speed error and output pitch angle signal are shown in Fig. 5. Trapezoidal functions are employed at both ends of the input and output variables to cover all the extremes range of values along with multiple triangular functions in between [49], [55], [56]

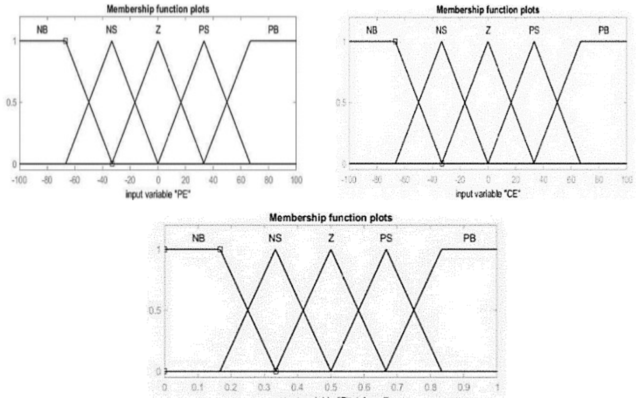

Fig. 5. Input and output membership functions

The structure of a standard PD fuzzy has been employed in which the controller has two inputs, error (E) and change in error (CE) with a single controller output [57], [58]. Despite that this controller has an acceptable performance especially when a constant wind speed is applied, the response starts to show a certain amount of steady state error when variable wind speed is used Thus, fuzzy PD plus I, shown in Fig. 6, have been designed where the output of the integral part is added to the output of the fuzzy PD controller.

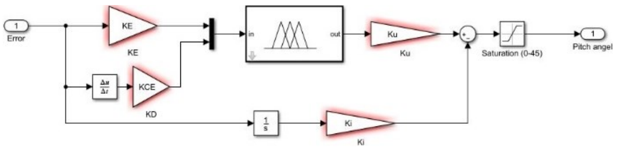

Fig. 6. Fuzzy PD plus I controller

This structure will enhance the controller ability to diminish the steady state error as well as dealing with the disturbances because it takes in consideration the error, change in error and accumulative error [59]-[61]. Manual tuning is applied to calculate the controller error gain (KE), change of error gain (KCE), output gain (KU) and lastly the integral gain (KI) that give the optimum performance. The simulations were repeated several times. Each gain was varied over a certain region while examining the system response at each run to provide a guide in choosing gain values. The best values of the controller gains are listed in Table IV.

TABLE IV. CONTROLLER'S GAINS

Gains	PD Fuzzy	PD Fuzzy + I
KE	1.5	0.15
KCE	1	2.1
Ku	40.5	115
KI		0.023

The overall block diagram of the fuzzy PD plus I controller with the wind turbine system is shown in the Fig. 7.

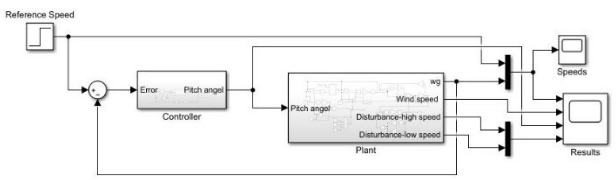

Fig. 7. Schematic Representation of the System's Block Diagram

IV. SIMULATIONS AND RESULTS

MATLAB simulink has been used for simulate and analyze the system design and performance. Firstly, the response of fuzzy PD controller has been examined. When the model used has constant wind speed, the fuzzy PD provides an acceptable performance. However, when variable wind speed is applied, the response starts to have a high steady state error in spite of accepted transient response. This is mainly due to the fact that neither P nor D is able to diminish the steady state error even though the proportional gain (P) has the ability to reduce it. Thus, an integral part has been added to form a PD Fuzzy plus I controller to eliminate the steady state error and even yields a better transient response at variable wind speed as shown in Fig. 8.

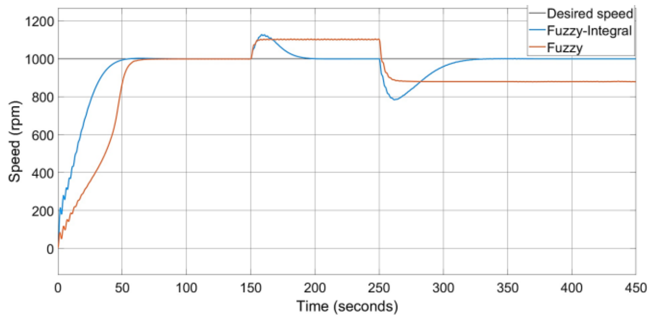

Fig. 8. PD Fuzzy Vs. PD fuzzy plus I responses

The transient and steady state characteristics of the PD and PD plus I controllers for variable wind speed input are summarized in Table V. It can be clearly noticed that system response equipped with PD plus I controller has a faster transient response in term of the rise time and settling time. Numerically speaking, they have been reduced by 30% and 22% respectively in compare with conventional PD controller. Regarding steady state error, PD controller has shown 12% error that has been completely eliminated after adding the integral part. These improvements are crucial to obtain smooth and steady power generation with a stable output frequency.

TABLE V. CHARACTERISTICS OF THE PD AND PD PLUS I CONTROLLERS

Characteristics	PD Fuzzy	PD Fuzzy + I
Overshoot (%)	0	0
Rise Time (s)	47.3	32.9
Settling Time (s)	57.6	44.7
Steady State Error (%)	12	0

To compare the performance of the fuzzy logic controller with that of other established control strategies, such as PID [30] and FOPID [27] controllers, it can be noticed that classical control techniques have succeded in producing a faster response in term of rise time and settling time with quite large overshoot and small steady state error. However, integral fuzzy controll reveals its potential advantages in wind turbine applications through the elimination of both overshoot and steady state error which prtects the turbine from mechanical stress and provide a steady power ouptut.

To test the relaibilty of controller, a variable speed set point was applied to the turbine control sysem while, wind speed is kept constant at 10 m/s. It can be noticed from Fig. 9 that the controller was able to track the desired speed successfully without any overshoot and a steady state error. This proves the consistent and efficient operation of wind turbines. Also, the ability to successfully tracks the desired speed without any overshoot and steady state error ensures the controller's capability of providing stable and accurate speed control which is important to maximize energy output of the wind turbine. In addition, this plays a vital role in safeguarding the safety and structural integrity of the wind turbine whereas overshoot can lead to mechanical stress and reduce the lifespan of equipment.

It is also important to monitor the change in pitch angle output while changing the desired speed. This guarantees that blade pitch angle adjustments are synchronized with speed changes, optimizing power generation while ensuring the angle within the allowable range.

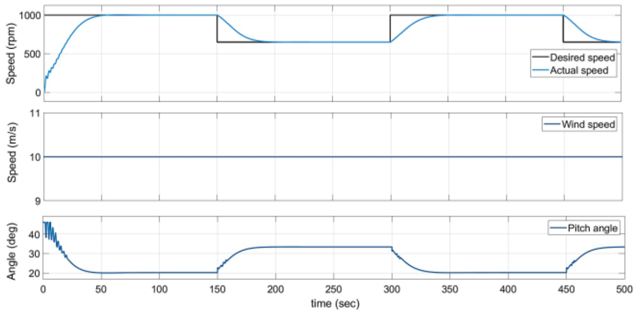

Fig. 9. Desired speed variation under constant wind condition

After testing the performance of the controller with variable desired speed at fixed wind speed, the next step is to test the controller ability to deal with variable wind speed. The change in wind speed is simulated as a step change with range of 8-12 m/s. Variable wind speeds can lead to unpredictability, efficiency issues, mechanical stress, and grid integration challenges. The controller's performance is crucial in this area, as it directly impacts overall energy production in wind farms. A well-performing controller, as shown in Fig. 10 with an overshoot less than 20% (15% - 17%), ensures optimized power capture, operational stability, and smooth grid integration. It translates into higher energy production, reducing costs per unit of energy and enhancing the economic viability of wind farms. Overall, it can be noticed that the controller was able to overcome the change in wind speed and keep the actual speed following the desired speed with small amount of overshoot.

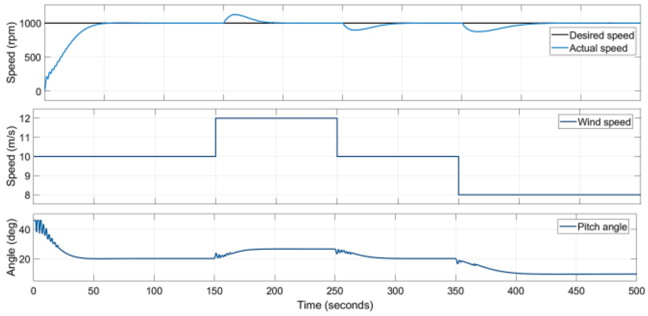

Fig. 10. Controller response to variable wind speed with pitch angle range

To further evaluate the reliability and robustness of the controller, the response of the wind turbine system is tested under several types of disturbances. This first disturbance is a sudden increase in the high-speed torque, simulating gusty winds or sudden load shock, of a value equal to 25% of its maximum range with a non-simultaneous change in the wind speed. These tests measure the controller's performance in dynamic conditions, ensuring its robustness for diverse operational scenarios. Explaining the rationale behind these disturbances and their real-world relevance provides a comprehensive understanding of the controller's capabilities.

Fig. 11 and Fig. 12 reveal the speed response during a sudden torque change along with the change in pitch angle respectively.

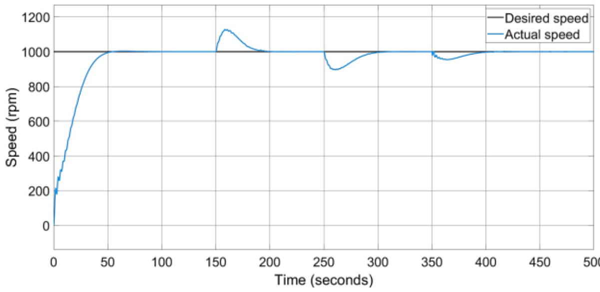

Fig. 11. Output response during high-speed torque disturbance

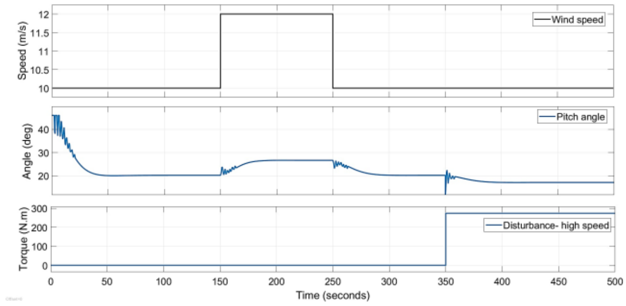

Fig. 12. Wind speed change, pitch angle and high-speed torque disturbance

Finally, Fig. 13 and Fig. 14 shows that the controller was tested to deal with a step change in wind speed while there are Asynchronous disturbances on high speed and low speed shafts with values of 25% of their maximum ranges.

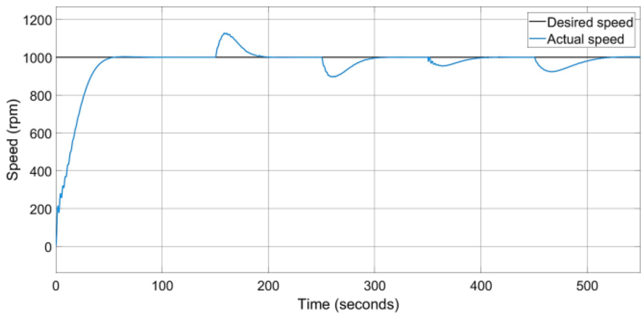

Fig. 13. Output response during high-speed and low-speed torque disturbance

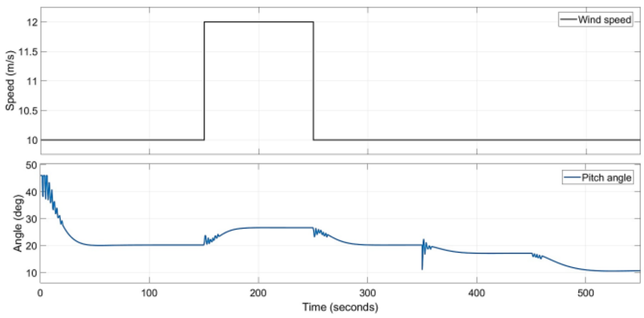

Fig. 14. Wind speed change and pitch angle responses at disturbances

It can be noticed that the fuzzy logic controller has succeeded to make a quick recovery of the wind turbine speed to the desired reference state. However, one peak has appeared at each torque disturbance input and its value is proportional to the total change in the torque value.

V. Conclusion

In this paper, a fuzzy logic controller has been designed to regulate the speed of wind turbine. Initially, a conventional fuzzy logic controller was applied which revealed an acceptable response of rotor speed and a fine regulation of the pitch angle. However, it failed to maintain rotor speed at wind turbulence of $\pm$ 2 m/s with relatively large steady state error of approximately $\pm$ 100 m/s in generator shaft's speed due to the fact that the derived turbine model is highly nonlinear dependent on wind speed. Therefore, integral fuzzy logic controller has been implemented to deal with wind fluctuation and external torque disturbances. The comparison between the proposed integral fuzzy and the traditional fuzzy controller showed that the proposed method was capable of attaining good tracking to the desired speed with a better transient response settling at roughly 45 s and zero overshoot and steady state error. Analysis and simulation have revealed that the fuzzy plus I controller was able to reject both wind speed and torque disturbances, that may come wind turbulences, load fluctuation or anonymous object hit by turbine blades, smoothly with a corresponding change in pitch angle of 5 to 10 degrees in order to maintain a constant rotor speed at a reference value of 1000 rpm. The main challenge in this work was the tuning of the controller's gains whereas the system response was very sensitive to parameter's change. Therefore, this work could be further improved through the implementation of an optimization technique, for instance GA or ABC, to tune the gain of the controller effectively.

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