Intelligent Fuzzy Optimized Control for Energy Extraction in Large Wind Turbines

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Abstract. In this paper an intelligent controller is designed to obtain the maximum power of a large floating offshore wind turbine. The control of these turbines is more complex due to the strong loads they are subjected to and the uncertainty that comes from the environment, mainly wind and waves, and from its non-linear dynamics. In this case, the control goal is to maximize the output power of the wind turbine by controlling the rotor speed. An incremental PD-type fuzzy controller has been implemented; it generates the pitch angle reference. The performance of this control scheme on the NREL 5 MW floating offshore wind turbine has been compared with the internal control that is provided within the FAST software. Results are encouraging, showing that the intelligent control strategy is able to produce more energy.

Keywords: Intelligent control · Fuzzy logic · Pitch angle · Floating offshore wind turbine · Renewable energy

1 Introduction

The demand for energy continues to grow and many countries have opted to promote renewable energies to eliminate pollution and carbon residues [1, 2]. Wind energy has proven to be a very efficient clean energy [3, 4]. But most common and widely installed onshore wind turbines (WT) have some limitations that have made it jump to offshore wind energy [5].

Within offshore wind turbines, floating offshore wind turbines (FOWT) have a series of advantages, such as eliminating the visual and acoustic impact, that they can be installed in deep waters, they take advantage of a stronger and more constant wind, etc. However, the fact that these turbines maybe much bigger due to the unlimited space in the high sea poses new control challenges. They are highly non-linear systems, with time changing parameters, and complex dynamics [6]. Besides, they are subjected to strong loads that produce undesirable vibrations [7–9].

This has led to investigate knowledge-based techniques to address the control of these floating turbines and to deal with the uncertainty that comes from both their dynamics and the environment (mainly wind and waves) [10].

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This paper addresses the problem of large turbines control. Specifically, it seeks to obtain maximum power by controlling the speed of the rotor, which in turn depends on the pitch control of the blades. An incremental fuzzy-PD controller has been designed for this purpose. It calculates the pitch reference that will feed the NREL 5 MW wind turbine model in order to control the rotor speed and maximize the energy. The simulation results with the fuzzy control strategy have been compared with the obtained for the same turbine defined within the FAST software (Fatigue, Aerodynamics, Structures, and Turbulence), with encouraging results.

The main contribution of this paper is the indirect rotor speed control by generating the pitch reference signal, similarly to [11], but using a fuzzy logic controller. Other papers are mainly focused on the pitch angle control, with conventional [12–14] or intelligent techniques [5, 15, 16].

The structure of the paper is as follows. Section 2 describes how the wind turbine performs. Section 3 presents de design of the fuzzy logic control scheme. In Sect. 4 results are presented and discussed. The paper ends with the conclusions and future works.

2 Wind Turbine Power Equations

We work with the offshore wind turbine NREL 5-MW, whose parameters are listed in Table 1.

Table 1. Wind turbine parameters [17].

Nominal output power	5 MW
Nominal wind speed	12.5 m/s
Blade number	3
Initial rotor speed	12.1 rpm
Generator nominal output	5 MW
Blade length	61.609 m
Cut in wind speed	3.5 m/s
Generator number	1
Tip Rad	63 m

The power that can be obtained from the wind is given by [4]:

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

Where P is the power (W), ρ is the air density (Kg/m^3), A is the area of the blades (m^2) and ν is the wind speed (m/s).

There is a limit of the theoretical maximum efficiency of a wind turbine (Betz limit), meaning that at most only 59.3% of the kinetic energy from wind can be used to spin the turbine and generate electricity. The amount of power that can be taken from the turbine is determined by the *Cp* coefficient. The *Cp* coefficient is a function of blade angle β and the blade tip ratio speed (TRS), λ [18]. Thus, the mechanical power that can be obtained is given by:

$$P_{\omega t} = 0.5\rho A v^3 Cp(\beta, \lambda) \tag{2}$$

There are different approximation of the power coefficient *Cp* of the turbine; in this work we have used the following [18].

$$Cp = 0.5176\left(\frac{116}{\lambda i} - 0.4\beta - 5\right)e^{-\frac{21}{\lambda i}} + 0.0068\lambda \tag{3}$$

The variable λi, that has no physical meaning, is determined by,

$$\frac{1}{\lambda i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{3\beta + 1} \tag{4}$$

The tip ratio speed λ is the relationship between the angular velocity of the blades and the wind speed, given by [2]:

$$\lambda = \frac{w.R}{v} \tag{5}$$

Where *w* (rpm) is the rotation speed of the rotor, and *R* the radius of the rotor (length of the blades).

Finally, the angle of attack of the blades that is going to be determined by the control law is:

$$\beta = \text{atan}\left(\frac{v}{w.R}\right) \tag{6}$$

3 Fuzzy Control Design

The control structure is shown in Fig. 1. An intelligent control system based on fuzzy logic has been implemented. It controls the rotor speed by means of the blade pitch angle trying to obtain the maximum output power.

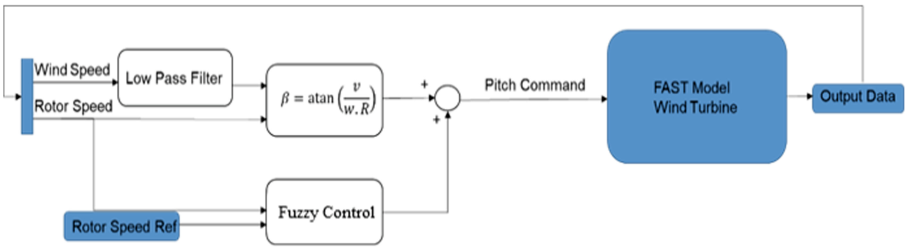

Fig. 1. Control structure

The fuzzy controller calculates the increase or decrease of the pitch angle of the blades, that will be the reference for the rotor speed control. We have implemented a

Takagi-Sugeno incremental Fuzzy-PD regulator that is equivalent to a PI controller [19]. The inputs of the controller are the error of the rotor speed, w_e (rpm), and the derivate, $\dot{w}_e$ (rpm/s), defined as,

$$w_e = w_{ref} - w \tag{7}$$

Where the reference w_{ref} has been set to 12.5 rpm, according to [11].

Three triangular fuzzy sets have been assigned to each input: Positive (green), Negative (blue) and Zero (red), as shown in Fig. 2.

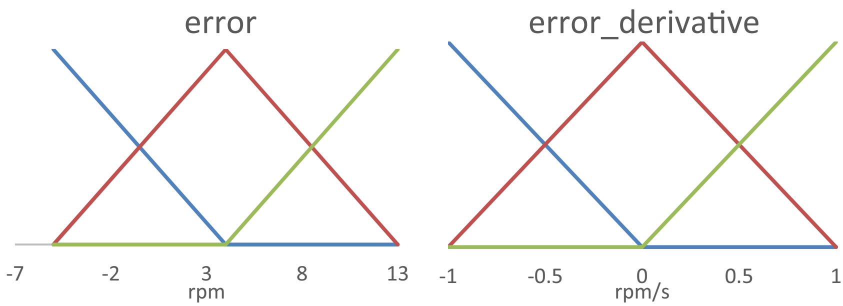

Fig. 2. Error (left) and error derivate (right) fuzzy sets. (Color figure online)

The error range is in the interval $[-5, 13]$ rpm, reaching its maximum at 12.5 rpm (constant generator torque) and the error derivate has been normalized between $[-1, 1]$ rpm/s to produce a smooth response.

The rules of the Takagi-Sugeno fuzzy controller are expressed as,

$$Rule(i) : if\ x_i\ is\ A_{i1}, \ldots, x_n\ is\ A_{in}\ the\ y_i = c_{i0} + c_{i1}x_i + \ldots + c_{in}x_n \tag{8}$$

Where the output is the pitch angle increment, Δu (°). They are listed in Table 2.

Table 2. Fuzzy rules of the fuzzy controller.

1. If w_e is negative and $\dot{w}_e$ is negative, then Δu is −20.
2. If w_e is negative and $\dot{w}_e$ is zero, then Δu is −10.
3. If w_e is negative and $\dot{w}_e$ is positive, then Δu is 0.
4. If w_e is zero and $\dot{w}_e$ is negative, then Δu is −10.
5. If w_e is zero and $\dot{w}_e$ is zero, then Δu is 0.
6. If w_e is zero and $\dot{w}_e$ is positive, then Δu is 10.
7. If w_e is positive and $\dot{w}_e$ is negative, then Δu is 0.
8. If w_e is positive and $\dot{w}_e$ is zero, then Δu is 10.
9. If w_e is positive and $\dot{w}_e$ is positive, then Δu is 20.

The rules for pitch angle were designed taking into account that absolute value of the maximum pitch angle for this turbine in FAST is 25º (typically it is between 0º and 10º).

4 Simulation Results

NREL FAST v8 [20] and Matlab software packages are used for the simulation. The proposed fuzzy controller is going to be compared with the internal controller of the Bladed-style DLL library embedded in the FAST simulator, test 24.

The wind profile is shown in Fig. 3. The average wind speed is 12.5 m/s. As it can be expected, it is a noisy signal. For that reason, a low-pass filter is applied (Fig. 1).

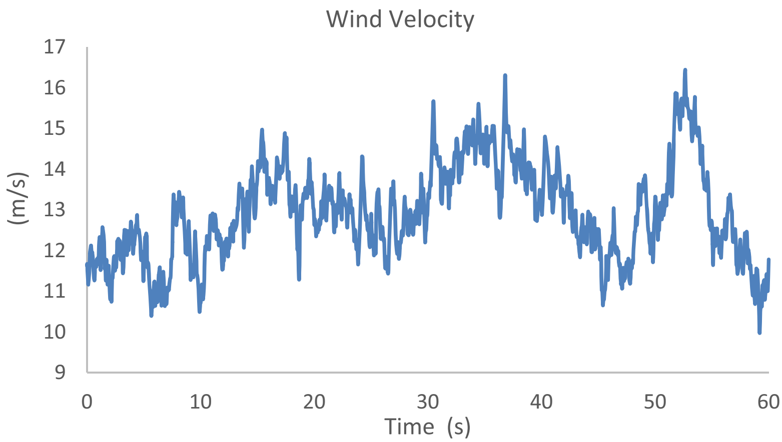

Fig. 3. Wind speed profile

In order to compare the response of the wind turbine with and without the fuzzy control strategy, the blade pitch angle with both approaches is shown in Fig. 4. It can be observed how from 22.5 s on the FAST regulator (red line) starts sending control commands to the blades to change the pitch angle, and the fuzzy controller starts at around 35 s (blue line).

According to the characteristics of the wind turbine (Table 1), the rotor starts at an initial speed of 12.1 rpm. The corresponding responses of both control schemes are shown in Fig. 5 (left) and a detailed view of it from 21.5 s on is presented in Fig. 5 (right), where the red line is the FAST response and the blue line the fuzzy proposed one. It is possible to see how the responses are quite similar until 30 s. At that time, the fuzzy controller starts to perform and then the difference between both controllers are noticeable.

As a result, the fuzzy controller extracts more power in comparison to the controller included in the FAST simulator (Fig. 6). Indeed, by analyzing Fig. 6 we can see that the rotor is able to extract more power from the wind than its maximum output power. However, operating above the rated power would induce excessive loads on the structure,

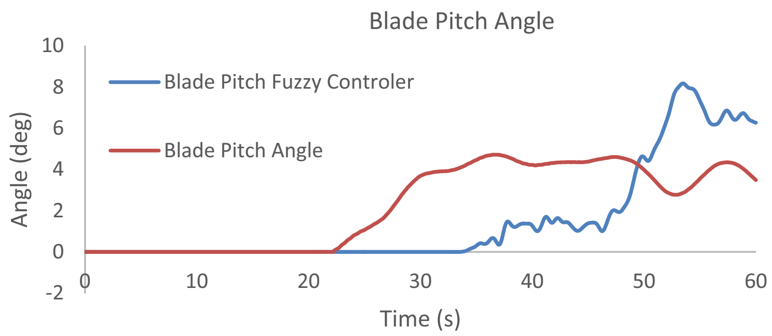

Fig. 4. Pitch angle. (Color figure online)

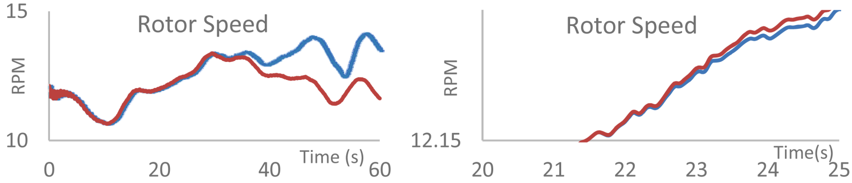

Fig. 5. Rotor speed (left) and zoom (right), blue line, fuzzy control; red line, FAST control. (Color figure online)

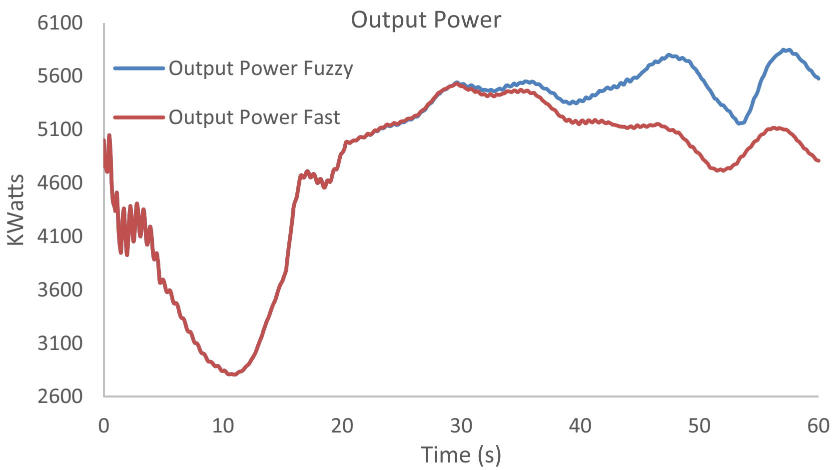

Fig. 6. Output power with FAST (red) and fuzzy (blue) controllers. (Color figure online)

compromising the life cycle of the turbine. In that case, the turbine should be shut down to avoid structural damage though.

In this simulation we have not done it in order to show how the fuzzy control is able to obtain more energy but this saturation of the actuators is included in the WT module.

5 Conclusions and Future Works

Floating turbines are oversized to better harvest the wind. This makes its control more complex. In this work a fuzzy system has been designed that obtains the reference of the pitch angle of a wind turbine to control the rotor speed. The goal is to obtain the output power that maximizes the energy efficiency of the wind turbine.

The fuzzy system implemented is an incremental PD fuzzy control. Its output feeds the NREL 5 MW turbine model.

The fuzzy controller shows a good performance, being able to deal with the non-linearity and uncertainty of the wind turbine. It response has been compared with a conventional controller that is embedded in the system under the same conditions, giving a smoother response and greater efficiency.

This work is a first approach to the application of intelligent control to floating turbines. As future works, different fuzzy type controllers [21] and adaptive fuzzy controllers could be tried to enhance the wind turbine response.

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