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Fuzzy Logic Tuning of a PI Controller to Improve the Performance of a Wind Turbine on a Semi-submersible Platform under Different Wind Scenarios

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Abstract: The integration of renewable energy sources in power systems, specially wind energy, is growing as environmental concerns arise in society. Nevertheless, the low amount of viable sites onshore or in shallow waters restricts the use of wind energy. In this sense, offshore semi-submersible platforms appear as an option, which in addition enables the integration of complementary elements, for instance wave energy converters. However, the complexity of the system increases due to the interactions between the platform movements and the wind turbine, and traditional control techniques do not enable to cope with these interactions in an easy way, hence limiting the efficiency of energy harvesting. Intelligent control techniques are an option with a great potential to take full account of the said interactions and to improve energy production efficiency. Still, it is required to have simulation models including those effects beforehand, so that the effects of a designed controller on the system can be evaluated. This paper presents an original fuzzy logic controller that tunes a reference controller, improving its performance according to a developed methodology that allows evaluation of controllers for wind turbines in semi-submersible platforms. The resulting fuzzy logic controller allows higher efficiency concerning mechanical loads in the system, electric energy production and tracking error of the speed reference.

Keywords: Control of renewable energy resources, Intelligent control, Fuzzy control, PI controllers, Control system design, Modelling and simulation of power systems, Marine systems, Pitch, Windmills.

1. INTRODUCTION

Increasing the share of renewable sources is a priority on the agenda of both developed countries and developing ones. In this recent trend, one of the most mature technologies, with higher potential of economic exploitation and large-scale integration in electrical systems is wind energy (Sahin, 2004; Leung and Yang, 2012). Specifically, marine wind farms (offshore wind) have advantages over land parks (onshore wind) regarding environmental impact and power obtained. Though, there is a shortage of adequate sites on the continental shelf, so locating wind turbines in deep water appears as an option. An alternative is its installation on semi-submersible platforms, as shown in (Castro-Santos et al., 2016), which enables additional activities as aquaculture or tidal energy.

It is expected that by 2030 the world's electrical energy consumption will be 31,675 TWh and that, in the moderate scenario, the wind energy installed capacity would reach 217 GW and 414 GW worldwide by 2020 and 2030, respectively (Sahu, 2018). In fact, installed wind power worldwide has increased from 93.55 GW in 2007 to 563.65 GW in 2018, and singularly the offshore power rose from 1.09 GW to 23.70 GW in the same period (The International Renewable Energy Agency, 2019), exceeding the predicted moderate scenario. For instance, in Spain, 16.6% of the electricity produced came from wind turbines in 2010 (Leung and Yang, 2012) and reached a value of 19.8% in 2018 (Red Eléctrica de España, 2019). Yet, the increase in the employment of electricity generated from renewable sources has led to the need of having controllers that regulate the instantaneous electrical power that is generated in this type of plant, as to increase the profitability of the investment and not to harm the quality of the electrical system they feed; particularly in wind energy for its great share of the energy mix. Currently, the main method used to do such regulation is the simultaneous control of the angle of attack of the blades, or pitch, and torque control using MPPT (Maximum Power Point Tracking) algorithms (Chavero-Navarrete *et al.*, 2019). While for the former the research community has not reached a consensus and there are different proposals, the latter is settled. Usually, the control techniques for the former are divided into four types: optimal TSR (Tip to Speed Ratio) search, closed-loop power control, ascending search control and intelligent control (Abdullah *et al.*, 2012). Among intelligent control techniques, fuzzy logic control is a good alternative to cope with variability (Santos, 2011), providing the required flexibility for wind turbine operation (Santos Peñas and Miranda Suescun, 2015). For instance, in (Simoes, Bose and Spiegel, 1997) a controller for a 3.5 kW wind turbine using three fuzzy logic controllers is developed, which increases the complexity and time needed to develop the control system. Moreover, the system tested is onshore and the power of the wind turbine is significantly lower than the commercial ones. The technique proposed in (Cárdenas and Peña, 2004), which consist of a PI controller together with a fuzzy one on a 2.5 kW wind turbine, shares these last two disadvantages. An application of a fuzzy logic controller together with a PI to an offshore wind turbine system with the NREL (National Renewable Energy Laboratory) of 5 MW is presented in (Lasheen and Elshafei, 2016), although which foundation and model have been used are not specified. Furthermore, an intricate process before designing the fuzzy controller is required, which is finally compared to the NREL reference PI controller. (Wakui, Yoshimura and Yokoyama, 2017) address a related control problem, though the type of semi-submersible platform is different and intelligent control is not employed. Another example of fuzzy control over a wind turbine with DFIG (Double Fed Induction Generator) is described by (Shahmaleki, 2018), where the wind turbine is onshore and the performance achieved is quite good but can be improved, as the reference generated by the controller is oscillatory. A comprehensive review of fuzzy logic control applied to wind turbines is presented in (Chavero-Navarrete *et al.*, 2019). Still, none of them faces the problem of pitch control when the wind is above the rated value in multi-MW wind turbines located on a semi-submersible platform.

Although control problems related to the generation of energy by wind turbines have been studied, those cases where these are found on floating structures have received little attention in the literature. The wind systems tested are limited to several kW of power, and the simulations, to onshore or offshore designs of several MW of power, but with fixed foundations.

This article presents an original fuzzy logic controller that improves the performance of the reference PI controller for a wind turbine located on a semi-submersible platform. Furthermore, a comparison between the baseline PI, an improved PI, a fuzzy logic controller already published in a previous work and the proposed fuzzy logic controller is carried out. The methodology is centred around the development of an integrated simulation tool and the definition of a set of performance indexes that consider mechanical loads, power generated and error in speed reference tracking.

For this purpose, in this article, the problem and previous proposed solutions that motivated the work are outlined in section 1 while in section 2 the system and the model that describes it are shown. In section 3, the key contribution of the article is presented: an original fuzzy logic controller. In addition, the integrated simulation tool and the performance indexes are depicted too. In section 4, for the four evaluated controllers, results obtained with this methodology are given and discussed. To end the article, conclusions are presented in section 5.

2. SYSTEM DESCRIPTION

The final goal is to control a real system composed of two wind turbines on a semi-submersible platform (W2Power concept by EnerOcean as lead developer, Fig. 1). As a first approach to the problem, simulations can be done with a single wind turbine in the centre of the semi-submersible platform. Following this methodology, the model of wind turbine that will be controlled is the NREL 5 MW (Jonkman *et al.*, 2009). This is an illustrative model of the wind turbines presently in development for offshore wind energy. In this sense, the NREL 5 MW has features that allows different studies to be done on it in the early phases of the development of new offshore designs. Equally, it could be used as a model to analyse control techniques and to test controllers.

Fig. 1. Offshore wind energy semi-submersible platform W2Power concept. Image of the scaled-prototype successfully tested during spring-summer of 2019 on Canary Islands, Spain. Source: EnerOcean S.L.

2.1 Equations

Main equations governing the behaviour of a conventional wind turbine (Lin and Hong, 2010; Kim, Chung and Moon, 2015) are introduced in this subsection. Wind energy is the kinetic energy that possess the air in motion, which affects the blades of the wind turbine and creates the spinning motion of the rotor. This rotational energy is transmitted to an electrical generator placed inside the nacelle, converting kinetic energy to rotational energy and subsequently to electrical energy through electromagnetic effects in the generator. The amount of power that can be harvested from the wind depends on the size of the wind turbine and the length of its blades (often characterized by the diameter of the imaginary circle they sweep during their rotation, giving rise to the sweep area). This amount of power harvested is expressed as the power of the wind that affects the sweeping area of the wind turbine multiplied by a coefficient C_p. This coefficient has a non-linear dependence with the TSR (normally noted as λ) and with the pitch (β), in addition to involve nine wind turbine constants that commonly only the manufacturer knows:

$$C_P(\lambda,\beta) = \frac{P_{harvested}}{P_{wind}} = = C_1\left(\frac{C_2}{\lambda_1} - C_3\beta - C_4\beta^2 - C_5\right)e^{-\frac{C_6}{\lambda_1}} + C_7\lambda \quad (1)$$

$$\frac{1}{\lambda_1} = \left(\frac{1}{\lambda - C_8\beta} - \frac{C_9}{\beta^3 - 1}\right) \quad (2)$$

Where the pitch is a variable controlled by the operator and the TSR is defined as the ratio between the linear velocity at the tip of the blades and that of the wind:

$$\lambda = \frac{V_{tip}}{V_{wind}} = \frac{\Omega_{rotor} R}{V_{wind}} \quad (3)$$

Both the C_p and the TSR are essential magnitudes in the control of wind turbines. As stated before, the wind power harvested by the wind turbine blades varies with the TSR and the pitch, so the wind turbine operator can alter the energy harvested by the windmill and accomplish a lower loss of power, a better use of the wind resource, and a longer lifespan of the equipment.

The power of the wind equals the product of air density, the swept area of the rotor, the wind speed cubed and a constant of value ½:

$$P_{wind} = \frac{1}{2} \rho_{air} A_{rotor} V_{wind}^3 \quad (4)$$

That is, the harvested power of the wind varies with the square of the radius of the rotor, so it is desirable to look for larger wind turbines. Knowing the harvested power and the speed of rotation of the low speed axis (usually calculated as the high speed axis, ω_{HSS}, measured with an encoder or similar, between the gearbox multiplication ratio, N_{gear}), it is possible to find the torque of the rotor and the low speed shaft (ω_{LSS}) produced by the wind, usually noted as T_{Aero}^{LSS}.

$$T_{Aero}^{LSS} = \frac{P_{harvested}}{\omega_{LSS}} = \frac{P_{wind} \times C_p}{\frac{\omega_{HSS}}{N_{gear}}} \quad (5)$$

Oppositely, there is a torque of the generator, or control torque. This is a variable that the wind turbine operator controls. In the rated operation of the wind turbine, it usually assumes a constant value equal to the rated torque.

$$T_{Generator}^{HSS} = \frac{P_{harvested}}{\omega_{HSS}} = \frac{P_{wind} \times C_p}{\omega_{LSS} \times N_{gear}} \quad (6)$$

Therefore, if the balance on the low speed axis is considered, in the rated state it rotates at constant speed (ideally). It must be taken into account that the torque of the generator is defined with respect to the inertia of the high shaft and that the wind torque is in relation to the low one.

$$T_{Aero}^{LSS} - T_{Generator}^{LSS} = I_{Drivetrain} \times \alpha^{LSS} \quad (7)$$

$$T_{Generator}^{LSS} = \frac{T_{Generator}^{HSS}}{N_{gear}} \quad (8)$$

Where $I_{Drivetrain}$ is the inertia referenced to the axis of low speed, since the two torques are also calculated with respect to that reference. Finally, α represents the angular acceleration of the reference axis.

Therefore, acting under the control variables $T_{Generator}^{HSS}$ and β (pitch), the behaviour of the wind turbine can be regulated in terms of extracted power, speed, etc.

2.2 Specifications

Most of the features come from the REpower 5M, a well-known commercial wind turbine, presenting the most important ones on Table 1.

Table 1. Main parameters of the NREL 5 MW.

Parameter	Value
Rated power	5 MW
Cut-in, Rated, Cut-out wind speed	3, 11.4 and 25 m/s
Rotor, generator rated speed	12.1, 1173.7 rpm
Rotor topology, number of blades	3, upwind
Rotor and hub diameters	126, 3 m
Hub height	90 m
Control	Collective pitch, variable speed
Drivetrain, ratio	High speed, multi-stage gearbox, 1:97
Efficiency	94.4%

2.3 Baseline PI controller

The control systems for wind turbines, as the considered one in the baseline (Jonkman *et al.*, 2009), are usually based on two complementary subsystems: collective pitch control of the blades and generator torque control. These two systems can be designed to work almost independently, being the objective of the former to adjust the generator speed when operating above the rated wind value, even if the measured variable is the generator speed. It is in this pitch controller, a PI with an ad hoc gain-scheduling law (Fig. 2), where room for improvement exists, achieving a better behaviour for the system through the use of intelligent control techniques, for which it is necessary to previously have a simulation and comparison methodology.

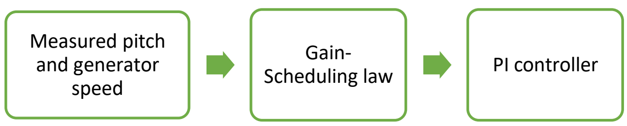

Fig. 2. Reference PI controller scheme.

On the other hand, the torque controller acts when the wind speed is below the rated value. Its objective is to harvest the maximum feasible power of the wind following an MPPT algorithm (Fig. 3), calculated by NREL based on the optimal TSR and C_p for a specific operation state.

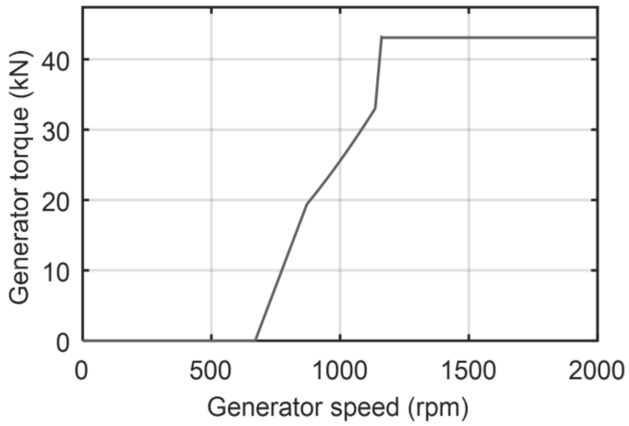

Fig. 3. Theoretical torque control law based on the MPPT algorithm.

3. METHODOLOGY

3.1 Integrated simulation tool

The development of an integrated simulation tool, depicted in Fig. 4, plays a key role on the methodology.

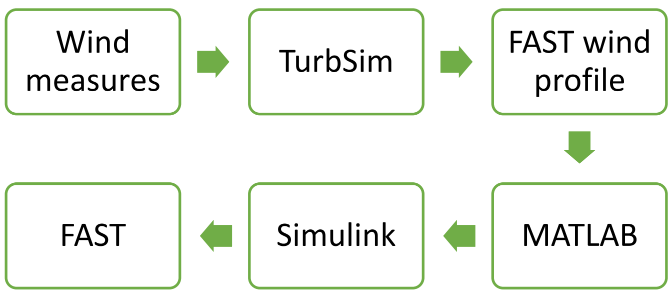

Fig. 4. Integrated simulation tool process of different stand-alone software tools.

To start with, available wind data of a chosen location is sent to TurbSim to obtain a wind profile in a compatible format with FAST. FAST is a Computer-Aided Engineering (CAE) tool developed by NREL to simulate the response of horizontal axis wind turbines to a given wind profile, among other inputs. These wind profiles are the key input to the used FAST model, integrated into MATLAB/Simulink, which gives the simulated outputs of the system. The employment of this integrated simulation tool allows for the design and evaluation of controllers for the selected wind turbine, in compliance with the well-known OC4 model (Larsen, T. J., Yde, A., Verelst, D. R., Pedersen, M. M., Hansen, A. M., & Hansen, 2014; Robertson et al., 2014).

3.2 Performance indexes

Usage of wind turbines on onshore sites exhibit some differences when compared to offshore platforms locations. The movement of the platform yield interactions with the wind turbine, producing oscillations that change the aerodynamic conditions for energy generation. Furthermore, these oscillations can also alter the mechanical loads at the base of the turbine, modifying the conditions for fatigue to appear. As stated in (Martynowicz, 2018), vibrations play a key role in wind turbines.

An important part of the methodology consists of three performance indexes, that already proved to be useful in (Rubio *et al.*, 2018), tailored to evaluate controllers for wind turbines in offshore platforms. These indexes resume the influence that an evaluated controller has on the mechanical loads, on the efficiency in the generation of electric energy and on the behaviour of the wind turbine compared with rated operation. In this sense, the indexes are described as follows:

- Mechanical loads index, MI. It provides an estimation of the influence of the controller on the lifespan of the platform. It is computed as the average of the absolute values of the reaction moment at the base of the wind turbine, for every time step, considering a rigid link.
- Generation index, GI. It measures the difference in MW between the generated electric power and its rated value. It is calculated as the average of the absolute value of this difference, for every time step.
- Speed index, SpI. It shows the difference between the speed of the electric generator and its rated value. It is calculated as the average of the absolute value of this difference, for every time step.

3.3 Proposed fuzzy logic controller

A PI controller that acts upon the error at the generator speed is the reference pitch controller. It holds a custom gain-scheduling scheme depending on the pitch of the wind turbine, adjusting the behaviour of the PI according to the current value of the pitch so, as the pitch grows, the gains of the PI decrease to adapt to the higher power sensitivity. This PI was improved by the implementation of an Anti Wind-Up ad hoc method (Zambrana-Lopez *et al.*, 2019).

The proposed fuzzy controller has been designed to substitute the gain-scheduling scheme, and at the same time to produce an improvement of the performance. The use of a fuzzy controller is a feasible alternative for this problem (Santos Peñas and Miranda Suescun, 2015; Rubio *et al.*, 2018), as it can consider the experience of the designer in the operation of wind turbines. Simultaneously, it can be enhanced incrementally, integrating new rules to consider the mechanical loads or the state of the electricity market, for example. The implementation scheme is shown in Fig. 5, and it can be seen that the fuzzy controller substitutes the gain-scheduling block. A critical decision was to drop the adjustment of the proportional gain, as no modification of it proved to offer better performance for the controller. This way, the proposed fuzzy logic controller modifies the value of the integral gain, while the proportional gain is held constant. This behaviour resulted in an augmented synergy between the integral part and the proportional one of the PI, which previously was not effective. In this sense, the proposed fuzzy logic controller enhanced the PI, and at the same time simplified it due to removing the gain-scheduling law.

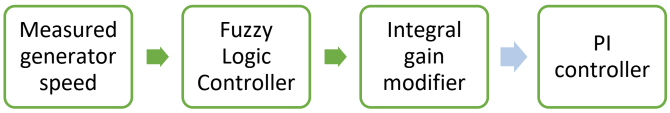

Fig. 5. Fuzzy Logic Controller implementation scheme.

In this manner, the proposed Mamdani fuzzy logic controller is implemented in MATLAB/Simulink with the operation parameters shown in Table 2.

Table 2. Methods of the proposed fuzzy logic controller.

Operation	Method
And	Min
Or	Max
Implication	Min
Aggregation	Max
Defuzzification	Centroid

For the generator speed input, membership functions were stablished heuristically according to different key speed values above the rated one based on the experience of wind turbine designers, normalizing them with respect to the rated generator speed. The names of the sets reflect this. As an example, L1 means a membership function centred on the first key range of speeds that are higher than the rated speed of the generator (Table 3).

Table 3. Membership functions (MF) of the input (Speed).

MF name	MF type	Defining points
UnderWn	Trapmf	[-3 -2 0.95 1]
L1	Trimf	[0.95 1 1.05]
L2	Trimf	[1 1.05 1.1]
L3	Trimf	[1.05 1.1 1.15]
L4	Trimf	[1.1 1.15 1.2]
L5	Trimf	[1.15 1.2 1.25]
L6	Trapmf	[1.2 1.25 2 2.5]

Once the behaviour of the gain-scheduling law described by NREL was studied, and flaws in the adaptation of the PI gains had been identified, the membership functions of the GK output were created, following the same nomenclature used in the input (Table 4).

Table 4. Membership functions (MF) of the output (GK).

MF name	MF type	Defining points
UWn	Trapmf	[0.99 1 1.5 2]
L1	Trimf	[0.5 0.6 0.7]
L2	Trimf	[0.4 0.5 0.6]
L3	Trimf	[0.3 0.4 0.5]
L4	Trimf	[0.2 0.3 0.4]
L5	Trimf	[0.1 0.2 0.3]
L6	Trapmf	[-1 0 0.1 0.2]

The rules were defined by mapping desired behaviour of the system with different outcomes through identified GK values from the NREL gain-scheduling law. Several adjustments were done after the first implementation, made possible thanks to the defined performance indexes and expertise from wind turbine designers. The seven rules that map the input to the output are shown in Table 5.

Table 5. Logic rules of the fuzzy logic controller.

If Speed is	Then GK is	Rule weight
UnderWn	UWn	1
L1	L1	1
L2	L2	1
L3	L3	1
L4	L4	1
L5	L5	1
L6	L6	1

The curve that shows the relationship between the input and the output summarizes the behaviour of the controller (Fig. 6) and was helpful in the aforementioned adjustment process of the fuzzy logic controller.

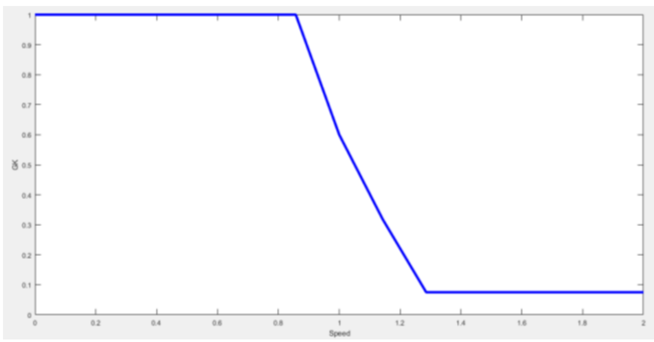

Fig. 6. Plot of the relationships between the input and the output due to the seven fuzzy logic rules.

4. RESULTS

The behaviour of the offshore platform under the proposed fuzzy logic controller has been evaluated using the methodology described above. The carried simulations have covered a broad range of operational wind profiles, through the employment of average wind speeds of 18 m/s, 15 m/s, 12 m/s and turbulence A in all of them (International Electrotechnical Commission, 2009) to portray the behaviour of the controller when the wind is near the value for the wind turbine to obtain the rated power with a 0º pitch, when it is slightly above, and when it is clearly over the rated value. It is at higher speeds when a pitch controller must present a good performance, since operators usually rely only on torque control for wind speeds below the rated value, as mentioned in the previous sections. As the most critical simulation is the one with 18 m/s mean wind speed, its graphics results are shown in Fig. 7 to Fig. 10 for the reference PI, the improved PI, the previous fuzzy logic controller and the proposed fuzzy logic controller, respectively.

In Fig. 7 it can be seen that the reference PI achieves a limited generator speed tracking error, yet it is noticeable.

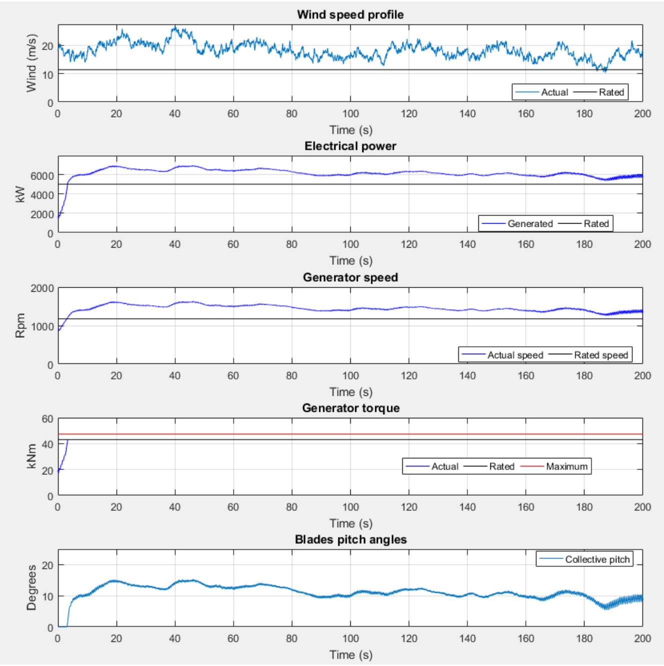

Fig. 7. System performance controlled by the reference PI controller under the 18 m/s A wind profile.

The improved PI, Fig. 8, shows a better performance as the generator speed tracking error is low in certain periods of the simulation. Still, the variability of the wind is not properly handled and sometimes the error grows rapidly. The previous fuzzy logic controller substitutes and outperforms the PI in the problem of achieving a stable response from the system, Fig. 9, yet the generator speed tracking error tends to be bigger than in the case of the improved PI controller (Fig. 8).

The proposed fuzzy logic controller arises as a better solution, being able to control the system under the simulation conditions, allowing for a steady response and a low generator speed tracking error (Fig. 10). Despite the fact that the novel controller improves the behaviour of the system, the complex interactions previously mentioned between the platform and the wind turbine cause periodic overshooting, yet these effects are greatly reduced by the use of fuzzy logic without the need to tune its parameters for each simulation even though each wind profile causes different interaction effects.

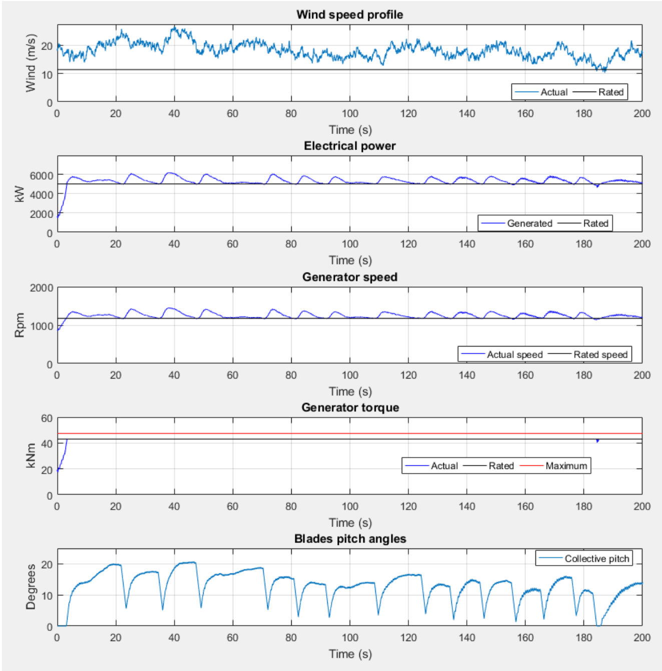

Fig. 8. System performance controlled by the improved PI controller under the 18 m/s A wind profile.

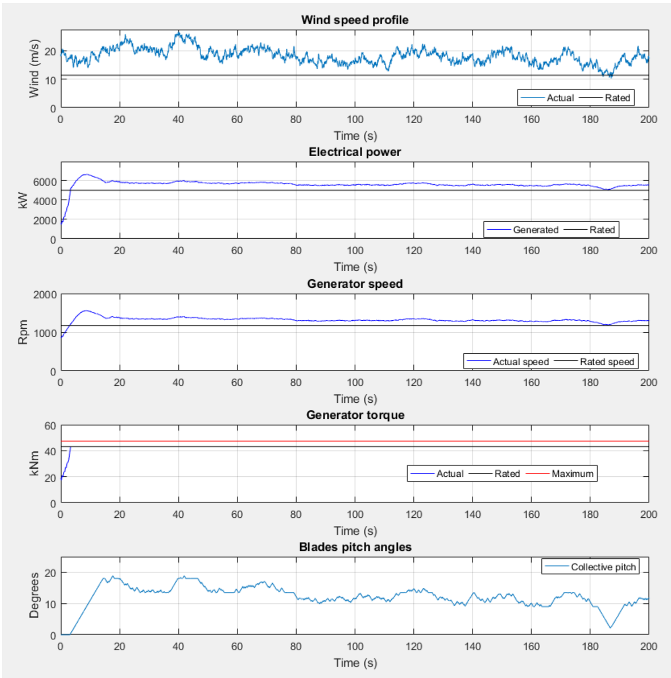

Fig. 9. System performance controlled by previous fuzzy logic controller under the 18 m/s A wind profile.

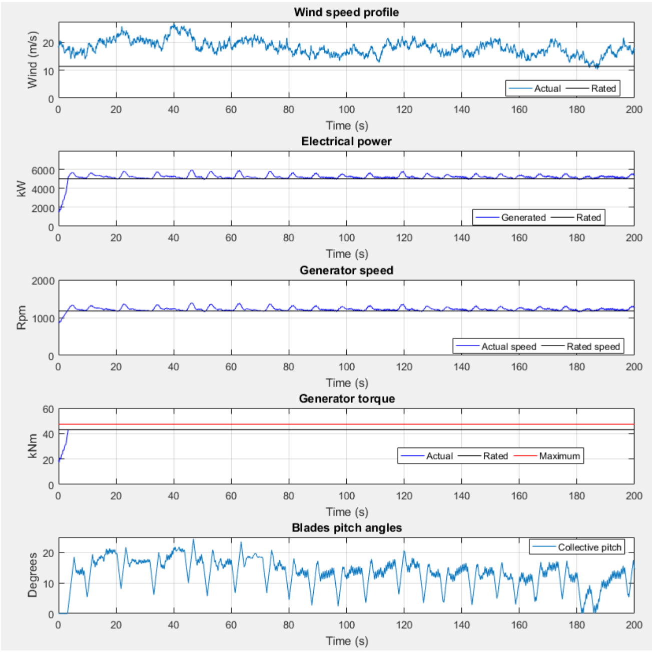

Fig. 10. System performance controlled by the proposed fuzzy logic controller under the 18 m/s A wind profile.

Although the curves show the response of the controllers, the proposed performance indexes provide an easier comparison of the respective performances. Table 6 to Table 8 present the indexes for all the studied controllers, for simulations with the aforementioned three different wind profiles.

According to the definition of proposed indexes, a lower value means a better performance. It should be noted that all controllers present a similar performance at 12 m/s. When the speed rises slightly above the rated value, the behaviour of the proposed fuzzy logic controller is better than that of the others. The difference is even bigger for 18 m/s. These results show that the proposed fuzzy logic controller offers a better performance in comparison to the other controllers for the different simulation cases, especially when compared to the reference PI. However, a fuzzy logic controller can be enhanced incrementally, adding new rules or changing its topology. Using the proposed methodology, and the proposed performance indexes, fuzzy logic controllers emerge as an attractive option to improve the efficiency of wind turbines. Although their performances are already good, they still present a great room for further improvement through the integration of the expertise of the wind turbine operator.

Table 6. Mechanical loads index (MN·m).

	12 m/s A	15 m/s A	18 m/s A
Reference PI	76.4479	71.6635	60.0260
Improved PI	76.3767	69.6505	53.8895
Previous fuzzy	76.6939	70.0338	55.9004
Proposed fuzzy	76.1020	69.2329	53.3247

Table 7. Generation index (MW).

	12 m/s A	15 m/s A	18 m/s A
Reference PI	0.7871	0.5132	1.1988
Improved PI	0.7854	0.2883	0.3808
Previous fuzzy	0.7813	0.3318	0.6653
Proposed fuzzy	0.7829	0.2271	0.2614

Table 8. Speed index (rpm).

	12 m/s A	15 m/s A	18 m/s A
Reference PI	53.5189	103.3224	275.4546
Improved PI	50.2477	51.6521	83.30070
Previous fuzzy	51.2965	61.9664	150.2268
Proposed fuzzy	47.7927	36.4260	55.40290

5. CONCLUSIONS

The design of controllers plays a key role in the performance of facilities, particularly in offshore wind turbines, as interactions amid oscillations of the platform and the windmill might decrease the lifespan of the facility and hinder the performance of the energy generation. Moreover, these complex interactions might perturb the quality of the power signal of the systems that they feed, creating room for improvement through the employment of intelligent controllers.

A fuzzy logic controller that considers these effects is presented in this article, capable of improving the behaviour of the system, taking into account mechanical loads in the platform, generation of electric energy and tracking of speed reference; according to a developed methodology for evaluation of controllers. This methodology can help the design of intelligent controllers, which seems to be an alternative with huge potential to enhance the performance and profitability of wind turbines in semi-submersible offshore platforms. An integrated simulation tool has been used alongside a set of performance indexes to evaluate different wind turbine controllers. Specifically, the reference PI, an improved PI, a previous fuzzy logic controller and the fuzzy controller proposed in this work have been evaluated by applying the methodology, which helped in the process of identifying flaws in the controllers' performance. This work contributes with the proposed fuzzy logic controller in solving these drawbacks due to the creation of synergies among the proportional and the integral component of the improved PI.

Future lines of work, as it is possible to carry an incremental development, include addition of wave energy converters on the platform or consideration of the current price of energy in the calculation of the speed reference. The integration of these factors might achieve a comparatively superb profitability of the initial investment. On the other hand, further enhancement of the fuzzy controller may achieve lower overshooting. An interesting possibility is to test another type of fuzzy logic controller such as those that alter the PI reference value.

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