Development of a three-bladed horizontal axis wind turbine with active control by using a programmable logic controller

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Abstract. For the increasing the physical efficiency, useful life and avoid accidents in wind turbines, it is very useful to implement a pitch control on the blades that help as an aerodynamic brake and orientation in the base to follow the wind direction. The main goal of this paper was to develop a digital controller on the wind turbine blades that allows to keep the constant angular velocity and monitor the orientation of the wind. A computer-aided design software was developed for allowing the aerodynamic analysis by using SolidWorks® software based on a flow simulation tool. On the other hand, a MATLAB model was created employing Simulink tool and the Simscape toolbox with typical data from a 2MW wind turbine whereas the electrical and mechanical dynamics and control feedback were calculated having as input parameters the wind direction and speed. Consequently, a prototype was designed in 3D which was implemented to make the different tests. For lab experimentation, a fuzzy control algorithm was developed in structured control language and then implemented using the S7-1200 PLC. The trials with programmable logic controller and the fuzzy algorithm were satisfactory, which could be a basis for the optimization of the performance of a three-bladed horizontal axis wind turbine.

1. Introduction
Renewable energies are of great help to meet the growing demand for electricity worldwide, wind energy can serve as a source of energy in remote places without connection to national home networks, which represent 51% of the national territory [1]. According to researchers, wind energy is an inexhaustible green renewable source of energy [2,3]. It attracts the world's attention due to its rich reserves, low carbon environmental protection, wide distribution, and other advantages [4,5]. The blade pitch control system is one of the essential components of the horizontal axis wind turbine since it allows to serve as an aerodynamic brake, being a cheap option, easy to maintain, and good performance [6].

On the other hand, it plays an important role because wind speeds can have abrupt changes that can decrease the useful life, increase the frequency in which maintenance must be carried out, and even create accidents, where the blades or the tower rupture instantly, as has happened repeatedly. Programmable logic controller (PLC) is an industrial electronic device that can also be used to develop advanced control systems [7]. Employing structured control language (SCL) it is possible to program on totally integrated automation (TIA) portal environment from Siemens®, a code based on conditional control structures that allow the establishment of fuzzy rules to follow the different operations regions and find the objective of keeping constant the angular velocity in the rotor [8].

In this study, a three-bladed horizontal axis wind turbine design was performed to improve the physical efficiency by using a logic program based on PLC with an embedded algorithm (fuzzy logic).
It should be noted, this research might be the start to determine other physical parameters that are useful for developing different strategies to enhance the horizontal axis wind turbine performance.

2. Classification of wind turbines
First, the existing types of wind turbines are described, and a brief description is made of how it extracts the power depending on the wind speed, the swept area, and the power coefficient in three-bladed horizontal axis wind turbines. The classification of wind turbines is shown below.

2.1. Vertical axis
The rotation axis of the blades is perpendicular to the ground where it rests. Its main advantage is that it does not require an orientation system to optimize generation, since regardless of the wind direction, it will always produce the same amount of energy. Among their disadvantages is that they are more likely to stop due to the lower inertia of their rotor and to fall off their anchor point, so they are not ideal for areas with strong winds. Because of their lower aerodynamic efficiency and smaller sizes, they produce considerably less energy than a horizontal axis [9].

2.2. Horizontal axis
The axis of rotation is parallel to the ground. They are the most used and in which this project will deal because they are the ones with the highest efficiency and uniform downforce.

2.3. Downwind
The air encounters the tower earlier than the rotor. A guidance system is not necessary, but instead, have lower efficiency than windward turbines.

2.4. Windward
The air encounters the rotor before instead of the tower, this means that there is no aerodynamic interference with the tower and thus have greater efficiency.

2.5. Power extraction
The extracted power can be expressed in the Equation (1).

$$ P_b = \frac{1}{2} \rho \pi R^2 C_p(\lambda, \beta) v^3, $$  

where $\rho$ denotes the density of the air, $R$ is the radius of the rotor, $v$ is the speed of the wind before interacting with the turbine, $C_p(\lambda, \beta)$ is the aerodynamic efficiency, which is a non-linear function of the speed-relationship tip (TSR) and $\beta$ which is the angle of inclination of the blade [10,11]. TSR is defined in Equation (2).

$$ \lambda = \frac{\Omega R}{v}, $$

where $\Omega$ denotes the angular velocity of the rotor, $R$ is the radius of the rotor and $v$ represents the speed of the incoming wind [11]. The implementation of pitch control in the blades, the control system for turbine pitch, and backup power supply of the pitch motor are represented in Figure 1.

3. Development of the wind generator
In this section, the different methods, models, and materials to design the three-bladed horizontal axis wind turbine with active control are described.
3.1. Aerodynamic design

For determining the general characteristics of the model through the velocity and flow trajectories parameters, a simplified model was developed in SolidWorks® that was tested with the flow simulation tool to know the behavior of the wind turbine under certain wind currents and mechanical loads (see Figure 2). Figure 2 illustrates the design of the three-bladed wind turbine which was done with the wind to windward as it is the one that produces the highest efficiency, with wind speeds between 5 m/s and 30 m/s, showing that the efficiency achieved with this design is slightly higher than 50%, close to the Betz limit, which is the maximum possible efficiency of 59.3%. The torque generated by a force in a section of the blade is proportional to the radius of the section to the rotation axis. In the initial part of the blades is where the greatest efforts are produced and there is a greater probability of rupture, so it must have a greater construction area.

3.2. Modeling and simulation

Figure 3 illustrates the model and simulation of the system which was done with the MATLAB 2017b version by using the Simulink tool and the Simscape mechatronic module [12], behavior. The model depicts eight different stages such as direction and speed block, controller, dynamic model of the blades, pitch and yam control, blades block, nacelle, and tower. All of them were combined to analyze wind turbine.

Figure 1. Pitch control on the blades.

Figure 2. Model of the three-bladed wind turbine.

Figure 3. Simulink model of the system.
3.3. Design and printing of parts of the wind turbine prototype

Figure 4 is divided into Figure 4(a) shows the SolidWorks design of the nacelle, which includes the coupling with the rotor, space where the bearing and the encoder are supported. It measures 18 cm long and 7 cm in diameter at the front. The weight was distributed in such a way that the center of mass coincides with the center of the base. Figure 4(b) illustrates the rotor design whereas the outside part is located in the spaces where the servomotors are supported to move the blades, the green area is an internal chamber where the cables that come from the servomotors connect with the cables of the moving part of the slip ring, and through which the axis of rotation passes. A sliding ring mechanism was necessary to move the cables rotationally and prevent them from moving, obtaining a permanent electrical connection of good quality (see Figure 4(c)), being able to control the servomotors that will be permanently rotating with the rotor.

![Figure 4. SolidWorks design of the nacelle. (a) CAD model of the nacelle, (b) CAD model of the rotor, (c) slip rings.](image)

4. Control system

The wind turbine control system consists of several sensors, actuators, and system composites of hardware and software where the latter processes the input signals from the sensors and output signals of the actuators.

4.1. Controller

The Siemens S7-1200 PLC was selected in this study to carry out the different tests because it is possible to program in SCL and ladder language, it has a great variety of blocks for mathematical operations, the processing capacity is 64 bits, it has inputs of high speed for the encoder, which was useful for the exact reading of the speed, as well as the outputs with PWM and analog inputs and outputs.

4.2. Pitch control system

Individual pitch control requires separate actuators on the hub for each blade. Therefore, there must be some means of transmitting energy to the rotating center to drive the actuators. This can be achieved by employing slip rings in the case of electric actuators, or a hydraulic rotary joint for hydraulic actuators.

For the design of the control system, it is necessary to obtain some mathematical relationship that allows knowing the plant based on the input and output of the system, for this, a characterization is made, where the wind speed can be simulated (from a fan), which generates a certain effect on the blades of the turbine, produce a response in the rotor in which the angular velocity is measured through an incremental encoder located inside the nacelle. The angle of the blades is changed using the continuous movement of the servomotors. Subsequently, it is possible to make the fuzzy rules based on the different regions of operations (see Figure 5) that adjust to the non-linearities of the system, and that makes the angular velocity be maintained at 30 rpm whether the wind speed causes this value to be exceeded or decreased. In the face of too strong winds, the rotation should be canceled. This Figure also shows four regions of operation depending on the wind speed are observed; the lowest at the cutting speed (I), between the cut and below the nominal speed (II), above the nominal speed (III), and the last one that exceeds the maximum allowed speed, where there must be no generation for avoiding excessive mechanical loads. The defuzzification of the inputs, the evaluation of the rules, and the defuzzification
of the outputs was carried out employing conditional control structures according to the Takagi-Sugeno methodology, as it is the most efficient one. To implement the S7-1200 PLC was appropriate to program with SCL block, which was used for the system simulation. The parts that makeup Figure 6 are described below:

- Blades: With a length of 23 cm, they are responsible for transferring the thrust produced by the wind to the rotor due to the difference in speeds between each of its edges.
- Rotor: This element is the most important as the blades rotate on it, and the sliding rings are supported.
- Gondola: Inside there is the rotation axis, the bearing, and the NPN type incremental encoder (negative positive-negative, therefore, when the transistor is activated, the input must be connected to a 24 V common to make the reading of a logical “1”).
- Tower: it is of cylindrical geometry, like those used in the wind industry.
- Base.
- Fan.
- S7-1200 PLC.
- Connection panel.

5. Results

Figure 7 depicts the movements obtained by the servo motor to control the electrohydraulic valve that controls the pitch in the blades to take the control of variations in wind speed during the simulation. Furthermore, it is observed that the setpoint is reached in all operating regions and that the over-elongations are small.
The generated power varies although the angular speed is controlled to get constant values and the torque variation depending on the wind speed, causing the captured energy to not always be the same. The results of the characterization of the prototype are shown in Figure 8 which is divide into Figure 8(a), showing that the system is highly non-linear. On the other hand, Figure 8(b) shows the encoder reading of the rotor angular speed when the nominal speed increases due to the increase in the wind speed, where the objective is to keep the readings at 30 rpm. The reaction time was less than 1 s.

Figure 8. Characterization of the prototype, (a) characterization of the plant, (b) response to an increasing of angular velocity.

6. Conclusions
The characterization of the proposed system allowed us to discover the attack angle of the blades, which must be between 70 °C and 90 °C. Angles less than these do not generate enough lift, so the blades do not move. Because of the flat face on the back and a saturation phenomenon, the angular velocity (rad/s) starts to decrease after 90 °C of the attack angle. The SCL allowed implementing the control rules with good performance, although they had to be simplified because the software did not support two-row matrix chains and did not do the calculations well. Therefore, programming should be as simple as possible, more advanced PLC's like the S7-300 or S7-1500 may allow better work with matrices and vectors, and apply more extensive programming. On the other hand, the performance of the PLC controller and fuzzy logic algorithm was good as the variations in wind speed in the simulation were small. Mechanically, the prototype fulfilled the objectives of the research, the improvements can be done with a higher budget, and the experience obtained with this study. Through the active control aerodynamic brake on the blades, loads were reduced and service life increased. This research can be expanded by introducing more advanced control methods with predictive control or infinite h and taking into account laminar wind flows and stochastic wind speeds. Besides, a more elaborate prototype can be created, involving an electrical generator that can measure the voltage and current that it produces to establish more complex control rules.

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