Condition Monitoring of Wind Turbine Pitch Controller: A Maintenance Approach

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Abstract – **Due to the wind power capacity energy grow exponential, interest in operation maintenance is increasing. A proper pitch controller must be designed to extend the life cycle of some wind turbine (WT) components such as blades or tower. The pitch control system has two main, but conflicting, objectives. On the one hand, it seeks to maximize the wind energy captured and converted into electrical energy. On the other hand, it seeks to minimize fatigue and mechanical load. Various metrics are proposed to achieve a compromise solution that balances these objectives. A WT of 100 kW is used to validate pitch control strategies.**

I.   INTRODUCTION

As a source of renewable energy, wind power capacity is increasing exponentially every year around the world. Figure 1 shows the massive increase in capacity since the start of the new millennium.
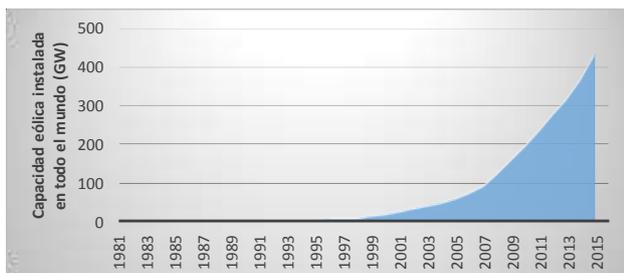
Fig. 1. Accumulative wind power capacity since 1981.

Wind turbines (WTs) have evolved from generating a few kilowatts in the 1980s to several megawatts today[1]. There are two main types of WTs: larger and smaller turbines. Each has its own advantages and disadvantages. Large WTs are generally placed together to produce electricity. These sets of WTs, called wind farms, can be installed on- or off-shore. Wind farms share common services and infrastructures with other electrical power types, for example, roads or equipment.

Small and medium sized WT generate less power. A small WT stretches a maximum of 200 m2 swept area [IEC 61400-2]. This swept area is approximately equal to 8 m blade radius. This type of WT generates between 1000 watts and 300 kilowatts [Canadian Wind Energy Association; https://www.aeeolica.org].

Although the nominal hub rotation speed usually reduces as the WT size increases, the WT power increases approximately by the square of the radius of the expanding WT. Figure 2 shows the approximate area and power.
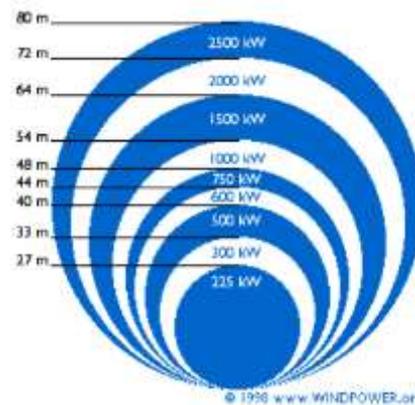

Fig. 2. Power increases by the square of the radius of the WT (source: EWEA 2009b, modified).

Although large WTs have attracted most of the attention of the manufacturing industry and the scientific community, small and medium sized WTs have several advantages. These include the following:

i) Their visual and environmental impact is less than large WTs because of their reduced size. Small and medium WTs normally use electric current power transmission and do not require special access. In some areas, certain orographic features may prevent the installation of large WTs; their construction may be prohibited or at the very least, an environmental study must be conducted. In contrast, small and medium WTs do not normally require environmental studies before gaining approval.

ii) They can be designed for and installed in places with poor wind speed characteristics, for example, discontinuous, turbulent or low wind speeds. The places with best WT characteristics are already occupied, but smaller WTs can be installed in less optimal locations.

iii) Installation of small and medium WTs encourages a

distributed generation concept and a decentralized electrical energy plan, for example, supplying electricity to a specific community. If one WT fails, the rest continue working.

(iv) In addition, smaller WTs can be integrated into urban structures. They can take advantage of existing urban infrastructures, such as access paths. This implies a reduction of direct costs because there is no need to explicitly build and maintain this type of infrastructure. Urban integration also facilitates a short distance between WT energy production and consumption, thus reducing electrical losses due to the joule effect.

While these advantages are generally understood, less is known about other possible advantages of smaller WTs. To fill this gap, this paper looks at small and medium sized WTs from the perspective of operation and maintenance (O&M).

The paper is organized as follows. Section 2 gives information on modelling of WT components used in the paper. Section 3 explains the control systems and methodology used to identify patterns in time series data. Section 3 gives some recent, novel optimization algorithms. The use of the proposed methodology is illustrated in a case study in Section 4. The last section offers conclusions and outlines possible directions for future work.

II. WT MODEL

A model can be considered a theoretical scheme, generally in mathematical form, of a complex system, elaborated to facilitate its understanding and the study of its behavior [2]. An exhaustive precision model involves excessive human and computational resources that must be justified; from the control systems point of view, there must be a balance between accuracy and computation time [3].

WT modelling requires knowledge from several scientific fields, including meteorology and atmospheric sciences.

This paper focuses on onshore horizontal axis WTs with variable speed controlled by pitch movement. This type of WT is composed of several subassemblies that can be modelled as aerodynamic, structural, mechanical, and electrical models. Aerodynamic models require the interaction between air flow and WT components exposed to wind to be characterized. It is necessary to have information about the materials used and the assembly and shape of the components. Mechanical models require information about forces and inertia to calculate the dynamic between rigid bodies. Finally, electrical models show the interaction between the electric generator (the source), the electric power converter (the conveyance) and the grid (the consumer).

A. Aerodynamic

The first aerodynamic aspect to consider at design

states resides on the total number WT blades. Although a WT designed with 3 Blades represents the dominant concept today, the first WTs are made with two blades as well as some offshore WT installed recently. WT designed with 3 Blades presents high efficiency. Number of blade solution is a balance between several goals: i) extra wind power is extracted as additional WT blade is added; ii) dynamic loads fluctuation is arisen by yawing operation performed. This phenomenon is decreased as extra blade is added; iii) as reduction of blade number, rotation speed is increased to achieve same aerodynamic efficiency. Noise normally is increased by speed growths; iv) add a blade involves additional burden to the WT structure and requires further design to withstand. Also, rotor increases the weight and wind needs extra effort at initial states; v) each blade needs to perform an appropriate maintenance routines. An increment of blade number implicates an extra maintenance cost.

Aerodynamic behaviour is characterized by WT blade shape. The radius of a WT blade is approximately estimated by half of rotor diameter. The main parts showed on figure xx are root, mid span and tip.
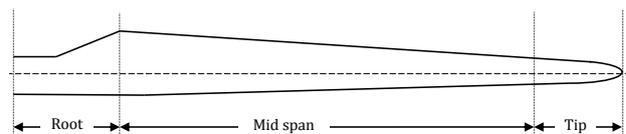

Fig. 4. WT blade.

The cross sections of a WT blade from the root to the tip are called aerofoil. Blades normally presents different aerofoil profiles at each distance. Figure xx represents the most characteristic points, segments and lines of an aerofoil. The 2d aerofoil produces aerodynamic forces (lift force, drag force and pitch moment) when a fluid moves through it. The angle between chord line and relative wind speed direction is called angle of attack. These aerodynamic forces fluctuate as a result of changes in angle of attack.
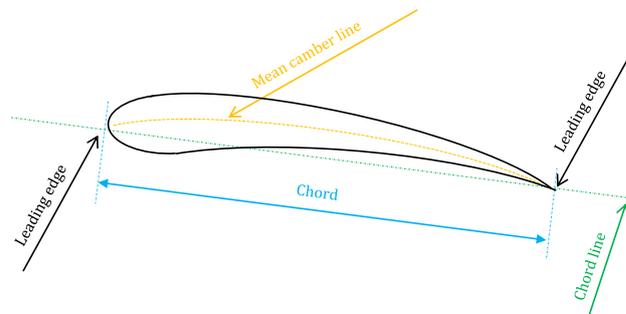

Fig. 4. Airfoil.

Pitch system is a mechanical, electrical or hydraulic device located at root blade to rotate blades longitudinally in both directions. Figure 5 show pitch angle WT blade rotation
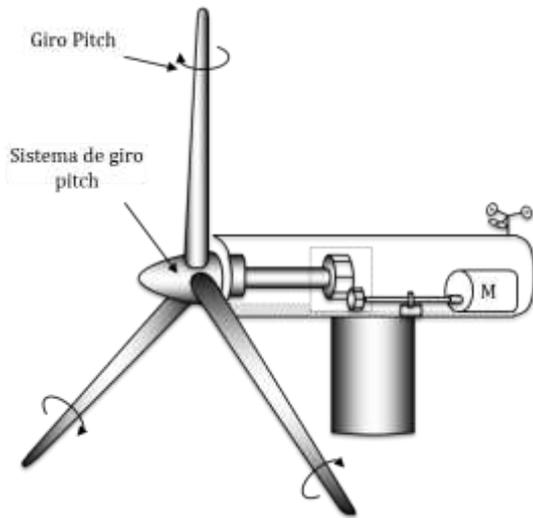
Fig. 5. Aerodynamic power coefficient.

The **Yaw system** is the system in charge of turning the tower to orient the WT towards the direction of the wind. It usually consists of a set of bearings connected between the tower and the gondola, rotating the gondola around the vertical axis of the tower, while the tower remains static.
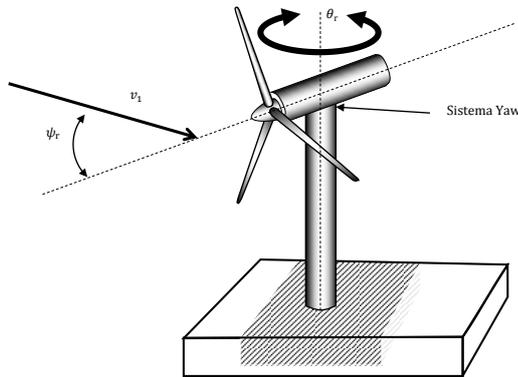

Fig. 4. Airfoil.

The aerodynamic model is defined by aerodynamic power coefficient denoted as C_P. [4]. This coefficient is calculated by means of computational fluid dynamics with accurate results. Another technique using certain assumptions and approximations is blade element theory. Aerodynamic power coefficient is frequently provided as a function of the tip speed ratio λ and the pitch angle β. The tip speed ratio λ is the relation between tip blade rotational speed and wind speed calculated by this equation:

$$\lambda = \frac{\Omega_r \cdot r_b}{v_1} \tag{1}$$

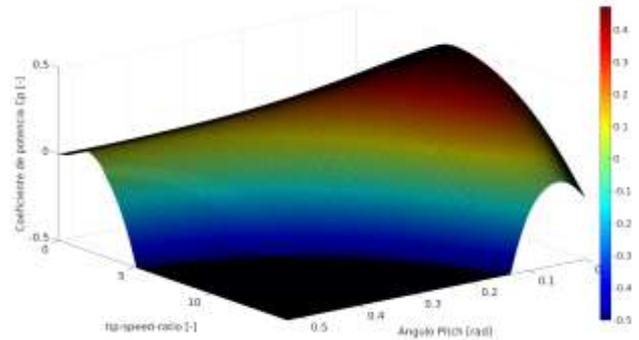. Figure xx shows the power coefficient.

Fig. 4. Aerodynamic power coefficient.

The mechanical power extracted by the WT is calculated by this equation:

$$P_r = \frac{1}{2} \cdot \rho_{Air} \cdot r_b \cdot \pi \cdot {v_1}^3 \cdot C_P(\lambda, \beta) \tag{1}$$

The force that the air exerts on the WT rotor is given by this equation:

$$F_T = \frac{1}{2} \cdot \rho_{Air} \cdot r_b \cdot \pi \cdot {v_1}^2 \cdot C_T(\lambda, \beta) \tag{1}$$

B. Structural model

The most important structural parts of what is composed are shown in Figure xxx.
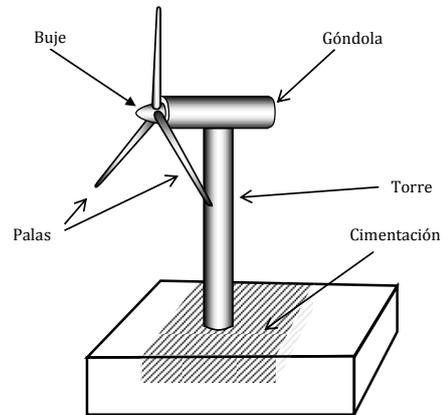

Fig. 4. Aerodynamic power coefficient.

Nacelle is a housing structure of mechanical and electrical components.

Tower is the structure that supports nacelle height. Normally, it is made of steel material and structured in tubular or lattice form. Also, there are small WT towers made of concrete [5].

Foundation is designed not only to transfer the vertical load but also to withstand the horizontal dynamic loads caused by the wind. WTs are tall and thin structures, but with a high horizontal load variable. The design of the foundations is calculated based on the tipping moment under extreme wind conditions [5].

Hub is the structural component that unites blades and

slow speed shaft;

Meteorological unit or "meteorological unit" is the system in charge of monitoring the speed and direction of the wind that the control systems use.

C. Mechanical model

Bedplate is the structure that supports mainly power train and power generator;

Main bearing improve slow speed shaft stability by reducing edges loads due to misalignment errors;

Slow shaft transmits the movement to gearbox. It must endure high torsional stresses;

The **gearbox** transfers the moment of force from slow speed shaft to high speed shaft;

High speed shaft transfers the moment of force from gearbox to electrical generator;

Brake system is fastened to High speed shaft and they are preserved by hydraulic pressure. However, when actuated for safety reasons, the pressure is released and the brake spring presses the assembly against the disc;
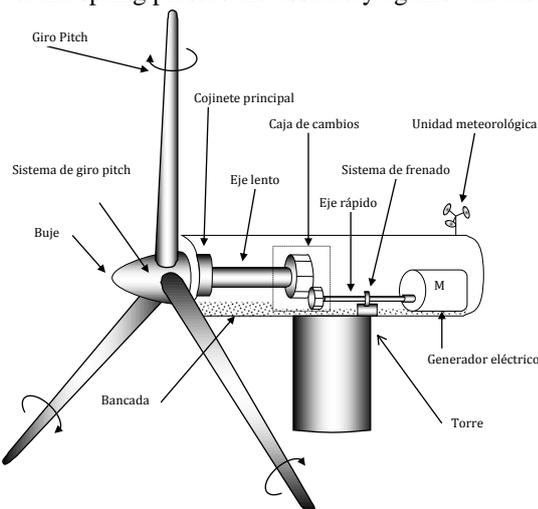

Fig. 2. Main WT components.

D. Electrical model

The electric model aims to transform the mechanical energy into electrical energy and pour it into the grid. Electrical system is mainly composed by electric generator and an electric power converter. There are various typologies of electrical system.

i) Squirrel cage induction generator is connected directly to grid. This is a synchronous electrical machine. WT operates as a constant speed and electrical torque cannot be controlled. Rotation speed is fixed by grid frequency (normally constant);

ii) Doubly fed induction generator is connected simultaneously to electric power converter as well as grid. The electrical torque is controlled by electric power converter. Although this generator is a synchronous electrical machine with external excitation, WT rotation

speed is variable.

iii) Direct-Drive synchronous generator is connected simply to electric power converter and them to grid. Electric torque is controlled normally by AC-DC-AC converter.

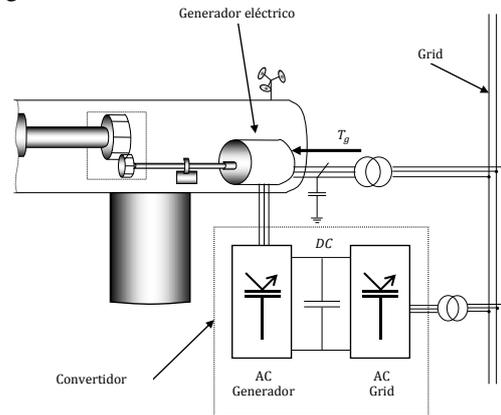Figure 2.51 shows an outline of the electric model

Fig. 2. Main WT components.

The electric generator and converter are modelled by an ordinary differential equation.

$$\frac{dT_g}{dt} = \frac{1}{\tau_{ps}} \cdot \left(T_g{}^* - T_g\right) \tag{1}$$

where T_g is the electrical torque setpoint, T_g is the current electrical torque and τ_{ps} is the electric power converter time constant.

III. CONTROL STRATEGIES

Pitch controllers are designed to do the following [6].

- They ensure high **availability** during long periods of operation, e.g., months.
- They guarantee **reliability** under harsh operating conditions, e.g., rain, snow or extreme wind speeds.
- They ensure precise **maintainability** to minimize WT downtime and maximize components' life cycles.
- They ensure **safety** to users and the environment, protecting them from non-desirable outcomes, e.g., electrical generator failure.
- They ensure **integrity**, e.g., such as WT blade fissure.

Availability, reliability, maintainability safety and integrity are targeted so that the failure rate over the life cycle of the components can be reduced. Figure xx shows the failure rate over time.
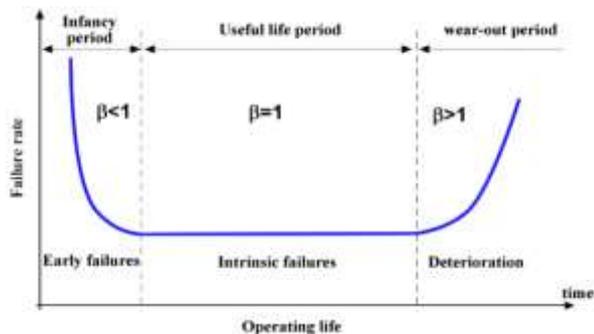
Fig. 2. Failure rate over time.

Although a WT is typically designed to operate for 20 years, some failures may occur over this period. The frequency of failures in WTs also varies with the scale and type. In general, failure rate increases with turbine size. The percentage of failures per component is shown in figure.
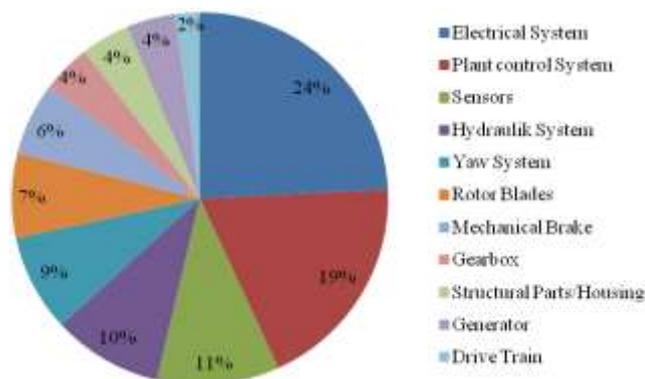

Fig. 1. percentage of WT failures per component.

A. Power curve

The electrical power supplied at different wind speeds is generally represented by a power curve graph. Polynomial and exponential curve graphs are the most common [7]. The power curve is given by WT manufacturers and calculated by averaged and normalized measurements [8]. Normally, four regions (I, II, III and IV) and two areas are represented [9]. Figure xx shows these divisions.
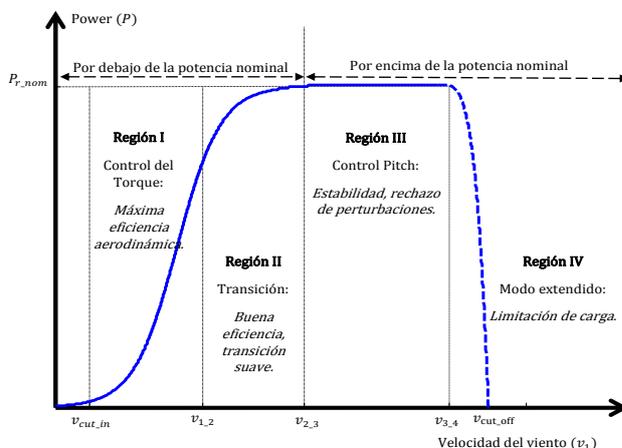

Fig. 2. Power curve.

Region I is the start-up region characterized by low wind speed, from v_{cut-in} to v_{1-2}. Maximum aerodynamic efficiency is achieved by setting the pitch at a minimum angle.

Region II is the transition region with low and medium wind speed, from v_{1-2} to v_{2-3}. A soft pitch controller is required because the electrical generator controller is the main control in this region.

Region III is the pitch control region characterized by high wind, from v_{2-3} to v_{3-4}. A full pitch controller is required.

Region IV is the extended region. Wind speeds are extreme, and the WT is stopped to avoid damage.

IV.   METRICS FOR EVALUATION

The pitch control system has two main, but conflicting, objectives. On the one hand, it seeks to maximize the wind energy captured and converted into electrical energy. On the other hand, it seeks to minimize fatigue and mechanical load. These objectives are quantified by the metrics proposed:

The first metric, maximize the energy delivered to the grid, is represented by this equation

$$\text{Obj}_1 = \min\{-P_r(t)\} \qquad (1)$$

Variations in the rotor angular speed must be avoided due to forces arisen. Figure xx represent an edgewise bending moment for rotor accelerations.

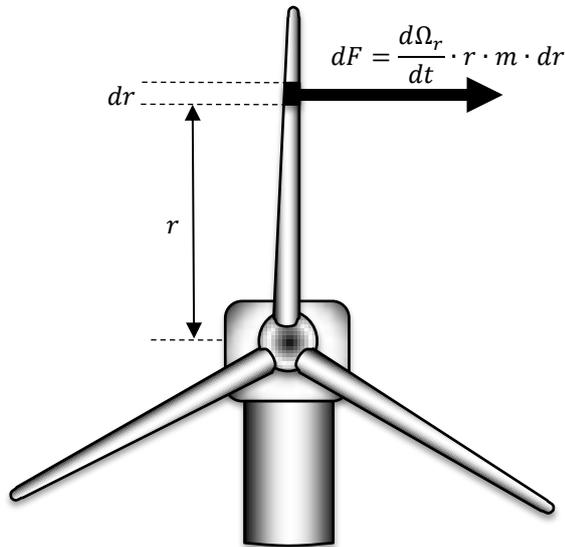$$dF = \frac{d\Omega_r}{dt} \cdot r \cdot m \cdot dr$$

Fig. x. Edgewise bending moment for rotor accelerations

WT maintains a constant rotor angular speed by means of rejects rotor angular acceleration. The second metric, minimize rotor angular acceleration, is represented by this equation

$$\text{Obj}_2 = \min\left\{\frac{d\Omega_r}{dt}\right\} \qquad (1)$$

iii) Variations in the pitch angle produce aeroelastic forces along the WT blade. Although pitch variations are needed to maintain WT in a precise state according wind speed fluctuation, some over actuations can occur. The third metric, minimize pitch angular speed, is represented by this equation

$$\text{Obj}_3 = \min\left\{\frac{d\beta}{dt}\right\} \qquad (1)$$

iv) Longitudinal force that the air exerts on the WT rotor must be reduced. To achieve an appropriate efficiency, most of wind energy must be transformed by blades into lift force instead of drag force (Longitudinal force). These longitudinal forces produce a flapwise bending moment on WT blades. The fourth metric, minimize longitudinal force, is given by this equation:

$$\text{Obj}_4 = \min\{F_T\} \qquad (1)$$

B. WT characteristics :

A picture of WT use case use is showed on figure xx. The typology is horizontal axis with 3 blades and the nominal power is 100kW.

Fig. 1. Turbec100Kw. (Courtesy of Argolabe SL)

The general specifications of this WT are showed in Table xx.

Table 1. General specifications.

Feature	Value
WT Axis typology	horizontal axis
Number of blades	3
Power	100kW
v_{cut_in}	3.5 m/s
v_{nom}	10.5 m/s
v_{cut_off}	20 m/s
Power control	Variable speed-pitch control

The aerodynamic specifications of this WT are showed in Table xx.

Table 1. Aerodynamic specifications.

Feature	Value
Blade radius	12.25
Number of blades	3
Swept area	400
v_{cut_in}	3.5 m/s
v_{nom}	10.5 m/s

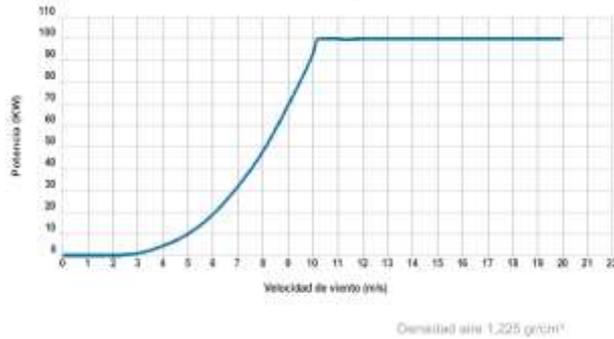|	
v_{cut_off}	20 m/s
Power control	Variable speed-pitch control

The power curve is showed in figure xx.

Fig. x. power curve of WT use case

The power train specifications of this WT are showed in Table xx.

Table 1. Mechanical specifications.

Feature	Value
Gearbox Multiplier	2 planetary stages
Gearbox transmission ratio	1:16:9
Electric generator	8-pole asynchronous induction

The electrical specifications of this WT are showed in Table xx.

Table 1. Electrical specifications.

Electrical converter	IGBT – total conversion
Output voltage	400 V
Output Electrical frequency	50 Hz

The structural specifications of this WT are showed in Table xx.

Table 1. Tower specifications.

Feature	Value
Tower height	36 meters
Typology	Tubular steel

V. CONCLUSIONS

Operation maintenance concentrates great interest due to WT is typically designed to operate for 20 years. Extend the life cycle of some structural components such as blades or tower is achieved by a proper pitch controller designed. A suitable aerodynamics-&-structural-&-mechanic-&-electric model of a 100kW WT is presented and main control strategies are showed to perform pitch controller simulations.

Four conflicting metrics are proposed to assess pitch controller tuning. These metrics condensate two main objectives: capture as much power as possible and reject fatigue as a result of not desired mechanical load.

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