Individual pitch control for wind turbine load reduction recognizing atmospheric stability

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1. Abstract

In this paper, the methodology for determining the optimal values of pitch angles considering the possibility of individual pitch control (IPC) in order to reduce stress on the wind turbines blades is presented. Unlike previous papers, the methodology developed in this paper aims to determine the reference values of the pitch angles in different atmospheric stability conditions, which directly affect the vertical wind speed profile. The stability of the atmosphere is determined by measuring the air temperature at two different heights, on the basis of which further estimation of vertical wind speed profile is conducted. The presented results show the optimal values of pitch angles for the same wind speed at turbine hub and various atmospheric stability and vertical wind speed profile for which average power output would remain same, but the stress on wind turbine blades would be reduced.

2. Keywords

Wind Turbine, Individual Pitch Control, Atmospheric Stability, Load Reduction

3. Introduction

The percentage share of renewable energy source (RES) in modern power systems is increasing every year. This predominantly includes wind turbines (WT) and photovoltaic systems. Further development of wind energy requires increasing the installed capacity of wind turbines, which also leads to an increase in its size. As the stress of the turbine depends on the wind speed, the increase of blades' length leads to the increase of dynamic loads due to changes in the stress of the turbine blades with a change in their azimuth angle.

This problem can be solved using individual pitch control (IPC) of WT. With the help of IPC, it is possible independently to control pitch angle of each turbine blade, in order to reduce the load changes on the turbine blades. The use of IPC is demonstrated in many research papers, books and thesis. The first concept of the load reduction by using IPC is presented in [1]. This paper suggests a model that uses data from sensors measuring asymmetrical load for determining the reference values of each blade pitch angle. The reference angles are determined with PI differential pitch controller. D – q representation of three blades pitch angles is presented in this paper. This concept is further analyzed in [2]. In [3], IPC of wind turbine is demonstrated on the load model developed in the same paper. Design and implementation of a proportional-integral-plus (PIP) control algorithm for IPC is proposed in [4]. In [5], the model for IPC including wake modeling is proposed. Basic elements of IPC are summarized in [6].

In this paper, a model that will perform IPC based on estimated vertical wind profile, which is on the other hand determined by estimating the atmospheric stability is developed. In contrast to previous studies in which the pitch angle is determined by measuring the current load, in this paper it is determined by estimating the wind profile. As the changes of pitch angle cannot be performed instantly, the model proposed in this paper enables forecast of reference pitch angle, which on the other hand improves performances of WT.

The paper is organized as follows: the methodology for estimating atmospheric stability and vertical wind speed profile is presented in Section 4. In Section 5, the aerodynamic model of wind turbine based on finite elements method is presented. Methodology based on GA for optimal IPC considering atmospheric stability is presented in Section 6. Results of the analysis are presented in Section 5, and finally main concluson are presented in Section 7.

4. Estimation of atmospheric stability

In order to apply the optimization model proposed in this paper, it is necessary first to assess the vertical wind speed profile. As the only known wind speed is the wind speed at the turbine hub, in order to determine the vertical wind speed profile, it is necessary to determine the atmospheric stability. After that, based on the Monin – Obukhov similarity theory, wind speed at an arbitrary height can be computed as:

$$v_2 = v_1 \cdot \frac{\ln(\frac{z_2}{z_0}) - \psi_m}{\ln\left(\frac{z_1}{z_0}\right) - \psi_m} \tag{1}$$

The atmospheric stability is considered through the parameter ψ_m. Parameter ψ_m can be calculated as follows:

$$\psi_m = 0 \tag{2}$$

$$\psi_m = -b_1 \cdot \frac{z}{L} \tag{3}$$

$$\psi_m = 2 \cdot \ln\left(\frac{1+x}{2}\right) + l\,n\left(\frac{1+x^2}{2}\right) - 2atg(x) + \frac{\pi}{2} \tag{4}$$

Equation (2) corresponds to neutral atmosphere, equation (3) to stable and equation (4) to unstable atmosphere. Parameters b_1, p and x are equal to $p_1 = (1 - a_1 \cdot \frac{z}{L})^{-p_1}$, $b_1 = 4.5 \div 6$, $a_1 = 15 \div 20$ and $p_1 = -\frac{1}{4}$. Parameter L represents Monin – Obukhov length and it is calculated with equation (5):

$$L = a \cdot z_O^b \tag{5}$$

Coefficients a and b can be determined by estimating atmospheric stability. Atmospheric stability can be estimated by measuring air temperature gradient. Table 1. shows Pasquill classes, atmospheric stability and corresponding coefficients *a* and *b* depending on atmospheric stability [7].

Table 1. Parameters of atmosphere based on temperature gradient

Temp. gradient (^{o}*C/100m*)	Pasquill class	Atmospheric stability	a	b
ΔT/ Δz < -1.9	A	Very unstable	-11.4	0.1
-1.9 < ΔT/ Δz < -1.7	B	unstable	-26	0.17
-1.7 < ΔT/ Δz < -1.5	C	unstable	-123	0.3
-1.5 < ΔT/ Δz < -0.5	D	neutral	0	0
-0.5 < ΔT/ Δz < 1.5	E	stable	123	0.3
ΔT/ Δz > 1.5	F	Very stable	26	0.17

Figure 1 shows vertical wind profile in terms of different atmosphere stability for the same wind speed at the height of 105 meters.

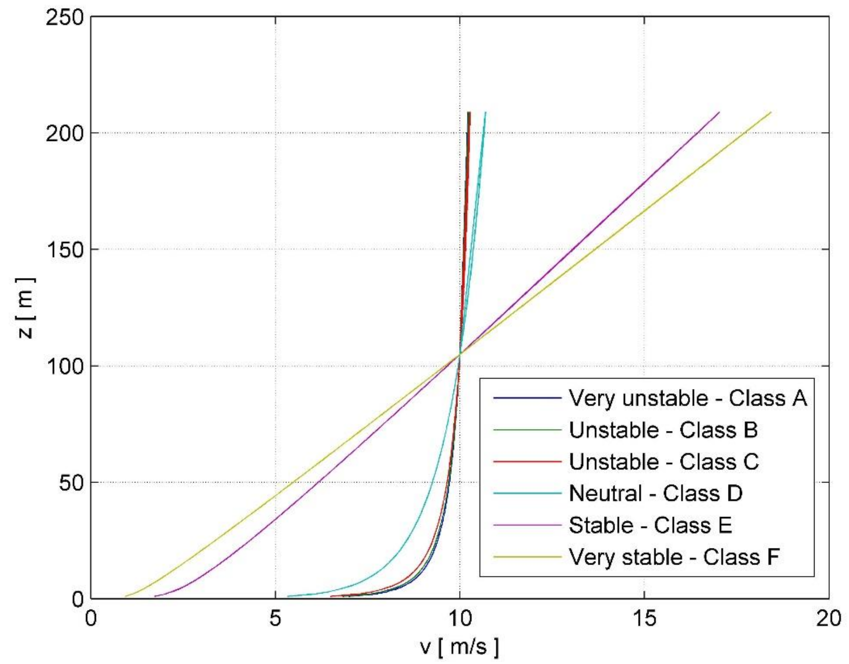

Figure 1: vertical wind profile in terms of different atmosphere stability for the same wind speed at the height of 105 meters

5. Wind turbine aerodynamic model

Based on the assessed vertical wind speed profile, it is necessary to make a model which would calculate the torque and load on wind turbine blade, depending on its azimuth angle, rotation speed and pitch angle. For that purpose, the model based on wind turbine blade element momentum theory is developed in MATLAB [8]. Figure 2 shows airfoil profile of wind turbine blade at a distance r from the rotor axis.

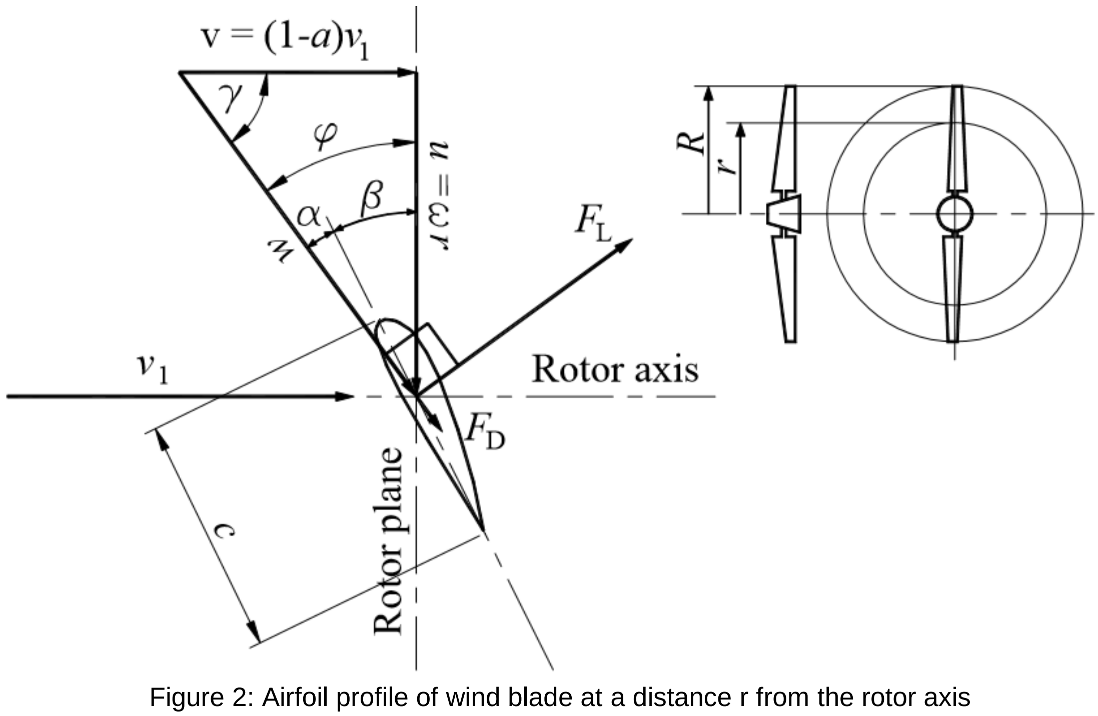

Figure 2: Airfoil profile of wind blade at a distance r from the rotor axis

Lift force and drag force acting on the wind turbine blade at a distance r are presented in equations (6) – (7):

$$f_l = \frac{\rho \cdot c}{2} \cdot V_{rel}^2 \cdot C_L(\alpha) \quad (6)$$

$$f_d = \frac{\rho \cdot c}{2} \cdot V_{rel}^2 \cdot C_D(\alpha) \quad (7)$$

Figure 3 shows lift and drag coefficients of NACA 23012 airfoil as a function of the angle of attack. In equations (6) – (7), ρ represents air density, *c* chord length, V_{rel} relative wind speed on the wind turbine blade, which is calculated in equation (8), and $C_l(\alpha)$, $C_d(\alpha)$ lift and drag coefficients that depends on the angle of attack. Angle of attack can be calculated from equation (9).

$$V_{rel} = \sqrt{(v_1 \cdot (1-a))^2 + (\frac{r \cdot w}{v_1}(1+a'))^2} \quad (8)$$

$$\alpha = atg\left(\frac{v_1}{w \cdot r} \cdot \frac{1-a}{1+a'}\right) - \beta \quad (9)$$

Tangential and axial force can be calculated from the equations (10) – (11).

$$f_t = \frac{\rho c}{2} V_{rel}^2 \cdot (C_L(\alpha) si\,n(\alpha+\beta) - C_D(\alpha)\cos(\alpha+\beta)) \quad (10)$$

$$f_a = \frac{\rho c}{2} V_{rel}^2 \cdot (C_L(\alpha)\cos(\alpha+\beta) + C_D(\alpha) sin(\alpha+\beta)) \quad (11)$$

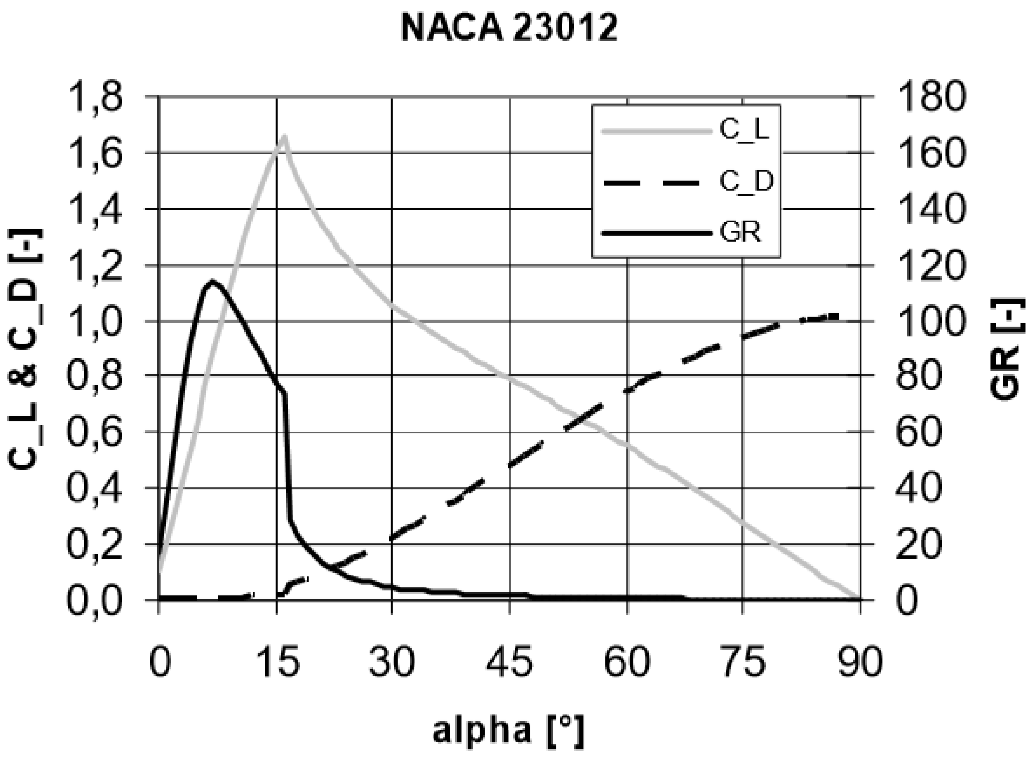

Figure 3: Lift and drag coefficients of NACA 23012 airfoil as a function of the angle of attack

From equation (10), wind turbine torque can be calculated as it is shown in equation (12). Equation (13) shows the total force acting on the wind turbine blade.

$$T = \int_0^R r \cdot f_t(r) \cdot dr \tag{12}$$

$$F_a = \int_0^R r \cdot f_t(r) \cdot dr \tag{13}$$

6. Optimization problem solution

In order to maintain the nominal power output of the wind turbine when the wind speed is higher than the nominal, it is necessary to reduce efficiency by increasing the pitch angle of blades. In this working zone, it is possible to reduce the dynamic stresses of blades using individual pitch control, under the condition that the mean output power remains constant. In order to determine the optimum values of the blade pitch angles for different azimuth angles, it is necessary to measure wind speed at the turbine hub and the temperature gradient. Knowing the temperature gradient it is possible to assess the atmospheric stability and vertical wind speed profile. Based on the estimated vertical wind speed profile, it is possible to determine the load on the turbine blade for different azimuth angles, which enables the optimal control of the pitch angles in order to minimize changes on blade stresses, equation (14), while the average power remains constant, equation (15). In this paper, optimum pitch angles are estimated for 24 azimuth angles, whereby it is assumed that the speed at the wind turbine hub remains constant and atmospheric stability is changed.

$$min\{\Delta F_a^{blade}\} \tag{14}$$

$$\sum_{i=1}^{3} M_i(t) \cdot w = P_n \tag{15}$$

As mentioned before, the model for determining the power and load of turbine blade for different azimuthal angles, based on wind turbine blade element momentum theory is developed. The proposed model uses wind speed at turbine hub, atmospheric stability, as well as the rotational speed of the turbine and pitch angle as the input data. Previously defined optimization problem can be solved by using genetic algorithm (GA). GA is an optimization algorithm whose work principle is based on the theory of evolution [9]. Its objective is to determine 24 pitch angles for different azimuthal angles, which would ensure the operation of turbine with a minimum load on the blades without changing average output power.

7. Results of the analysis

The proposed methodology is demonstrated on the next example. Nominal power of wind turbine is 2 MW. The hub height is 105 m and rotor diameter is 120m. It is assumed that wind speed at turbine hub is 15 m/s. For neutral atmosphere, it is calculated that reference rotation speed is 1 rad/s, and pitch angle is 2.8^o. The determination of optimal pitch angles depending on the azimuth angle of wind turbine blade has been carried out. Azimuth angles are oriented in the clockwise direction, where the zero angle is assigned to the bottom position of wind turbine blade. Analysis have been carried out for 6 different cases: Pasquill stability class A – very unstable atmosphere, Pasquill stability class B – unstable atmosphere, Pasquill stability class C – unstable atmosphere, Pasquill stability class D – neutral atmosphere, Pasquill stability class E – stable atmosphere and Pasquill stability class F – very stable atmosphere. Figure 4 shows optimal pitch angles of wind turbine blades depending on azimuth angle. Figure 5 shows axial forces acting on wind turbine blades depending on azimuth angle for two cases: system without individual pitch control and system with individual pitch control. Figure 6 shows optimal pitch angles in polar coordinate system.

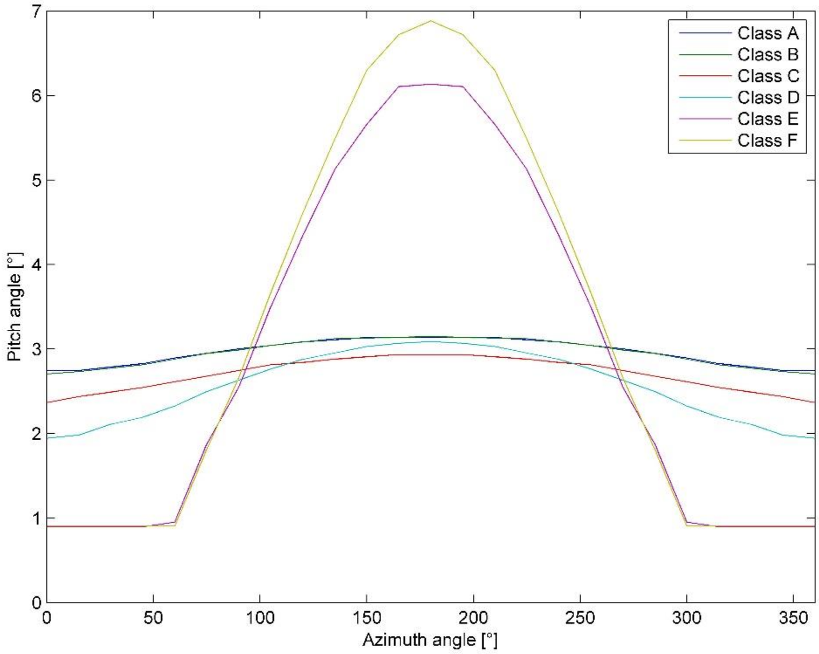

Figure 4: Optimal pitch angle in the system with IPC for different Pasquill classes

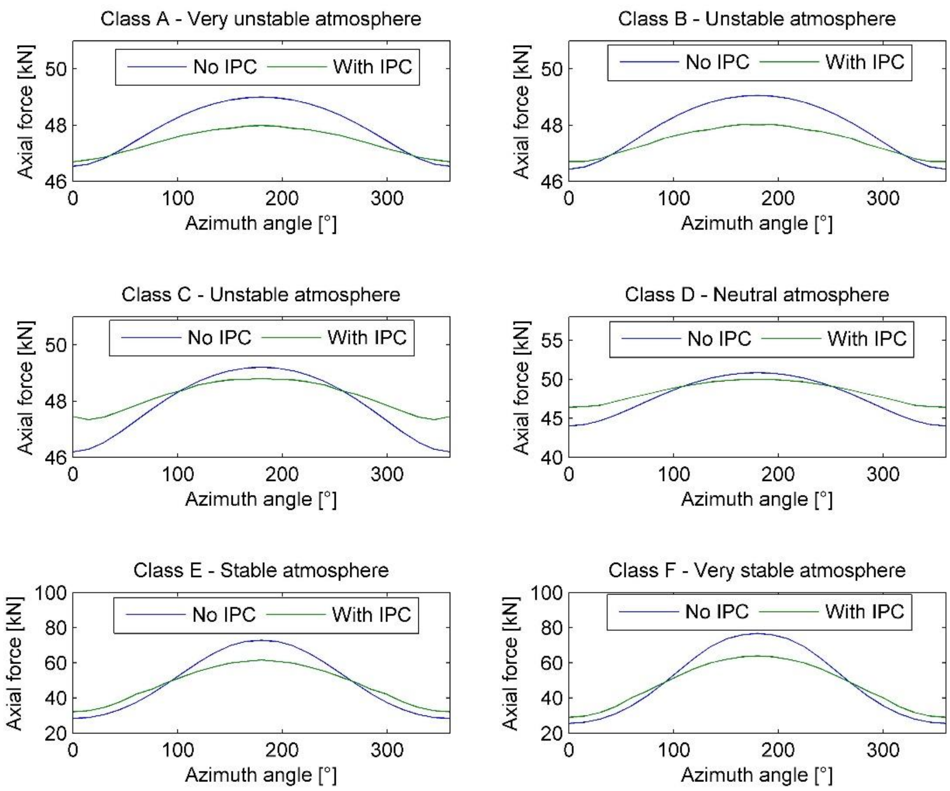

Figure 5: Axial forces for different atmospheric stability, with and without IPC

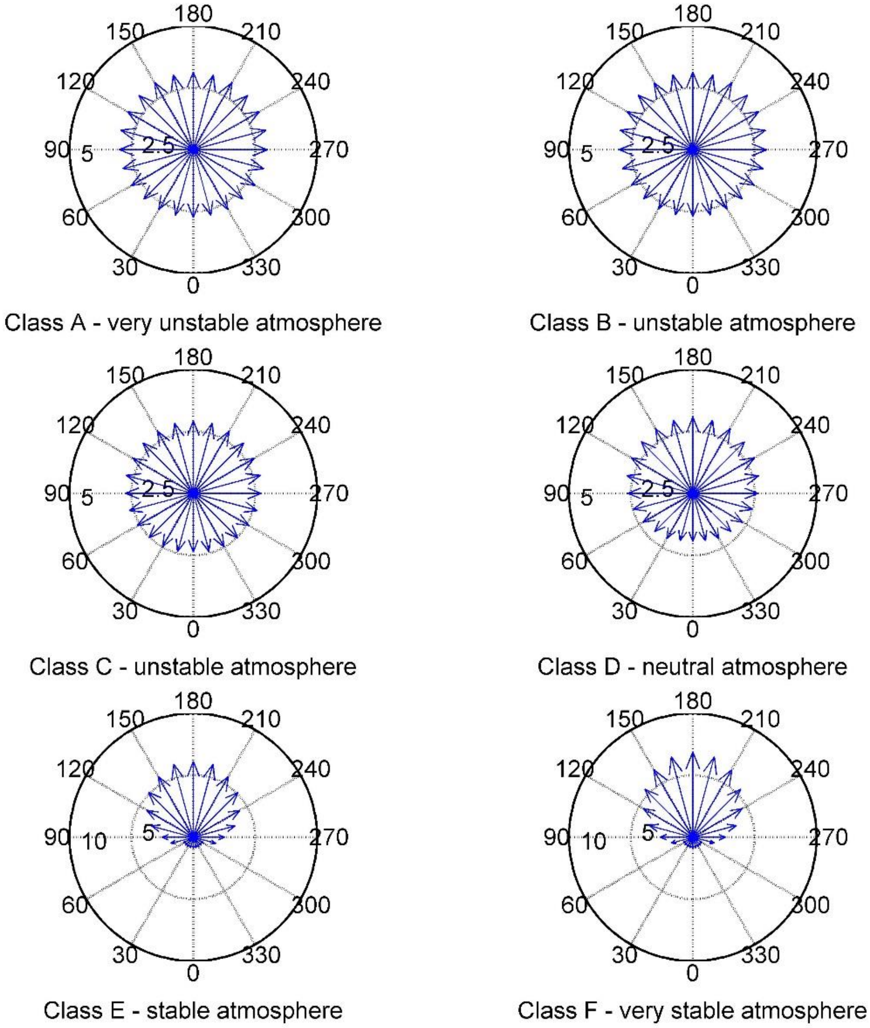

Figure 6: Optimal pitch angles in polar coordinate system

8. Conclusion

In this paper, we developed a methodology for determining the optimum pitch angle of the wind turbine blades in conditions of different atmospheric stability in order to reduce the load on the turbine. The proposed algorithm is capable to estimate atmospheric stability and vertical wind speed profile based on measured wind speed at the turbine hub and temperature gradient, and then, considering those information to implement individual pitch control in order to minimize the load on the turbine, without changing the average turbine output power. Results obtained from simulations confirm all the advantages of the proposed algorithm.

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