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Comparison and Choice of MPPT of Wind Turbines Based on Mechanical Wind Generator Speed Control

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Abstract

This article aims at the choice of a good adequate control strategy for the regulation of the Maximum Power Point Tracking (MPPT) of the wind turbines, in order to evaluate and appreciate the dynamic and static performances of the aerogenerators in accordance with the requirements predicted by builders. Also, given the random behavior of the wind, the strategy aims to guarantee the wind turbines a production of energy in quantity and quality, allowing among other things to reduce the mechanical wear on the aerogenerators. To do this, the proposed approach allows the comparison between the MPPT strategy without speed control and the MPPT strategy with mechanical speed control of the wind turbine. The results show that unlike the MPPT without speed control, the strategy with speed control is the most efficient in terms of speed, accuracy, and stability. And is also the strategy best suited for the choice of the model and the development of the advanced controls of the aerogenerator envisaged. The results are obtained using MATLAB/Simulink software.

Keywords: Maximum Power Point Tracking (MPPT), Wind Generator, Wind Turbine, Mechanical Speed, control strategy

Introduction

In general, there are mainly two approaches aimed at optimizing the energy produced at the level of the aerogenerator of a wind station. The first approach is based on the regulation of the mechanical speed without knowledge of the characteristic curve of the efficiency (or power coefficient denoted Cp) of the wind turbine. This approach is often less encountered or neglected; because it is considered less reliable because it leads to unstable results; hence the increase in mechanical stress, the decrease in energy efficiency and the degradation of the quality of the power developed by the wind turbine [1]. Also, there is an increase in the complexity and cost of implementing the so-called approach without knowledge of the Cp curve. However, the second method based on mechanical speed regulation with knowledge of the Cp curve, improves the first approach by offering two possible control strategies, namely [2]: MPPT structure with rotation speed control; and MPPT structure without rotational speed control. Therefore, we are interested in the study of these two structures of MPPT, because we have noticed that the choice of an MPPT strategy by researchers, often lacks rigor and delicacy which consequently deprive us of knowledge of the real model and the optimal use of the performance of the aerogenerators envisaged. Moreover, given that there is always a match between the performance of mathematical models and that resulting from the practical data of manufacturers; we recommend in this work, to always resort to a rigorous comparative study between the MPPT structures before operating the choice of a control strategy that suits us best. This, in order to evaluate and appreciate the static and dynamic performance of wind turbines taking into account the stable and/or random behavior of the wind. In addition, the MPPT control

strategy aims to guarantee the wind turbines a production of mechanical power in quantity and quality in order to also allow the reduction of mechanical wear on the aerogenerators. Among other things, the objective of this work also concerns the validation of the mathematical model of a wind turbine considered in accordance with the requirements given by manufacturers. To do this, we propose a comparative study between the MPPT strategy without speed control and the MPPT strategy with mechanical speed control of the wind turbine subjected to two random and non-random wind profiles. Validation studies of modeling results are carried out using MATLAB/Simulink software. The document is presented as follows:

- The first part concerns the methodology: this detail the mathematical simulation model of the aerogenerator of the wind power station envisaged. In addition, the various models of synthesis of the commands by estimation of the mechanical torque and by Proportional and Integral actions (PI) are exposed respectively for the structure of MPPT without speed control and for the structure of MPPT with control of the speed of rotation of the turbine.

- The second part is the phase of results and discussions of the comparison simulation between the two studied MPPT structures.

- The third part is devoted to conclusions.

Mathematical Simulation Models of An Aerogenerator of The Wind Station with MPPT Regulation

Development of mechanical energy on the wind turbine

Figure 1 is presented with the aim of mathematically translating the behavior of the stresses related to the mass forces, along the transmission shaft of the mechanical energy of the wind turbine on the rotor of the electric machine of a wind system. To do this, the expression of the mechanical power (P_{aero}) available on the shaft of the aerogenerator, can be written [3,4]:

$$P_{aero} = 1C_p(\lambda,\beta)\rho\pi R^2 V^3 \quad (1)$$

The aerodynamic torque represented as in the Figure 1, has the expression [5, 6]:

$$C_{aero} = \frac{P_{aero}}{\Omega_{turbine}} = \frac{C_P(\lambda,\beta)\rho\pi R^2 V^3}{2\Omega_{turbine}} \quad (2)$$

were, β: Blade orientation angle

Mathematical model of the speed multiplier

The multiplier which adapts the slow speed of the turbine to a fast speed of the generator as in Figure 1 is defined by the following multiplier gain (G) [4-6]:

$$G_{aero} = \frac{C_{aero}}{C_g} = \frac{\Omega_{mec}}{\Omega_{turbine}} \quad (3)$$

Ω_{mec}: Generator shaft rotation speed G: Multiplier gain or coefficient

Cg: Mechanical torque

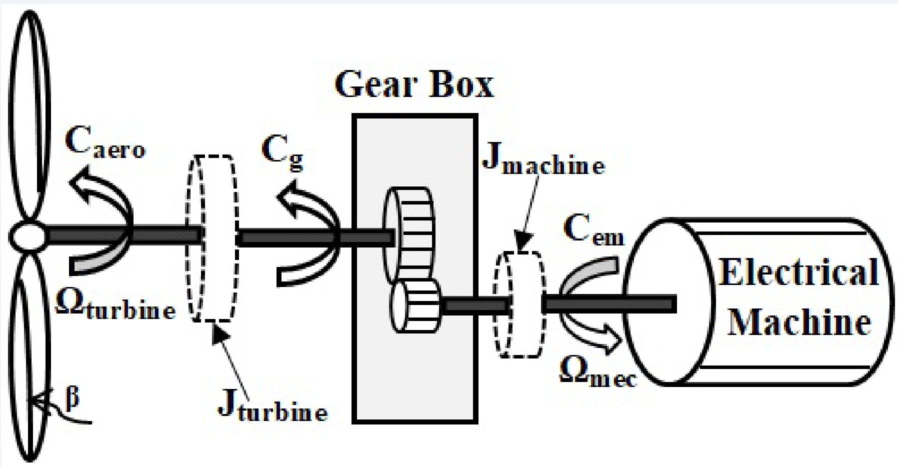

Figure 1: Mass forces on the mechanical energy transmission shaft of the turbine.

The expression of the mechanical power available on the shaft and at the rotor of the machine can be written:

$$P_{mg} = \frac{1}{2} C_p(\lambda,\beta)\rho\pi R^2 V_1^3 \quad (4)$$

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Equation of the mechanical energy transmission shaft to the generator

In principle, the distribution of the total moment of inertia (J) on the rotating shaft can be written [4]:

$$J = \frac{J_{turbine}}{G^2} + J_{machine} \quad (5)$$

Where, $J_{turbine}$ and $J_{machine}$ are respectively the moments of inertia on the turbine and on the rotor of the machine. s

Modeling the transmission of mechanical energy can therefore be summed up in the following Equation 5

$$J = \frac{d\Omega_{mec}}{dt} + f\Omega_{mec} = \sum C_{torques} = C_g - C_{em} \quad (6)$$

f: Coefficient of friction

Typical simulation model of a 2MW wind turbine (6)

Validating a model of the aerogenerator consists first in simulating a characteristic model of choice, which conforms to the dimensioning of a wind turbine that already exists in practice. Then, a comparative study between the two main types of MPPT regulation will allow us to adopt or choose the most appropriate MPPT strategy for the study considered.

Wind turbine modeling

As a general principle, remember that the theoretical efficiency of wind turbines, also called power coefficient C_p, corresponds to the ratio between the recoverable mechanical power on the shaft of the aerogenerator P_{aero} and the power of the wind P_{wind} crossing the turbine, whose expression is written [3]:

$$C_P = \frac{P_{aero}}{P_{wind}} \quad (7)$$

However, in practice, the mechanical efficiency of a wind turbine is characterized by its power coefficient noted $C_P(\lambda, \beta)$. The latter is defined according to climatological conditions such as the density of the air (ρ) and the behavior of the wind in contact with the blades of the wind turbine, thus referring to a relative wind speed called specific (λ). In addition, the efficiency $C_P(\lambda, \beta)$ also depends on the morphology of the blades or the geometric shapes of the turbine defined in terms of length or radius (R) of the blades, the angle of orientation of the blades or pitch angle (β), and the total number of rotor blades [4]. As a result, wind turbine manufacturers rely on experimental and/or practical tests to produce documentation of turbine characteristic curves that can be used to define a mathematical approximation of the power coefficient specific to each wind turbine. However, even if the coefficient $C_P(\lambda, \beta)$ changes from one turbine to another, the literature also teaches us that the difference between the characteristic curves or models of the turbines is often negligible in most applications [6]. As part of the study presented in this document, we were interested in an approximation of the power coefficient Cp, whose expression is used in many research works to better characterize a wind turbine, and is defined as follows [2,5-8]:

$$C_P(\lambda, \beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)\exp\left(-\frac{C_5}{\lambda_i}\right) + C_6\lambda \quad (8)$$

Where, C1 = 0.73, C2 = 151, C3 = 0.002, C4 = 13.2, C5 = 18.4, C6 = 0

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} \cdot \frac{0.035}{\beta^3 + 1} \quad (9)$$

We thus deduce the specific speed or speed ratio as follows:

$$\lambda = \frac{\Omega_{turbine} R}{V} \quad (10)$$

V: The speed of air movement as it passes through the blades.

By rearranging the expressions of equations (2), (3), (6), (8) and (10), the model of the wind turbine block diagram is determined, illustrated by Figure 2.

Simulation of the characteristic model of the 2MW turbine

The parameters used for the simulation of the model of the wind turbine of Figure 2, come from a large number of research works that exploit the documents of wind turbine manufacturers [2,9-11]. Therefore, we choose to use the parameters of a 2MW turbine, given in Table 1 in appendix [5,11]. Validation via the Matlab/Simulink software, of the model of the wind turbine illustrated in the Figure 2, first concerns the simulation of the efficiency of the model of the turbine alone by disconnecting the blocks of the multiplier and the mechanical shaft. Therefore, Figure 3 gives us the result of the simulation representing the

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curves of the power coefficient (C_p), according to the variations of the specific speed (λ) and the pitch angle (β). We can deduce from the curves of the Figure 3; this rated performance of the turbine as follows:

For a nominal wind speed of V = 11.2 m/s, at β = 0°, the value of the maximum power coefficient is $c_{p\max}$ = 0.4408 and the optimum specific speed obtained is λ_{opt} = 5.7601, the manufacturer's data in the Table 1 in appendix. In addition, we can see clearly in the fig. 3 that, the turbine efficiency (C_p) decreases with increasing pitch angle or pitch angle (β).

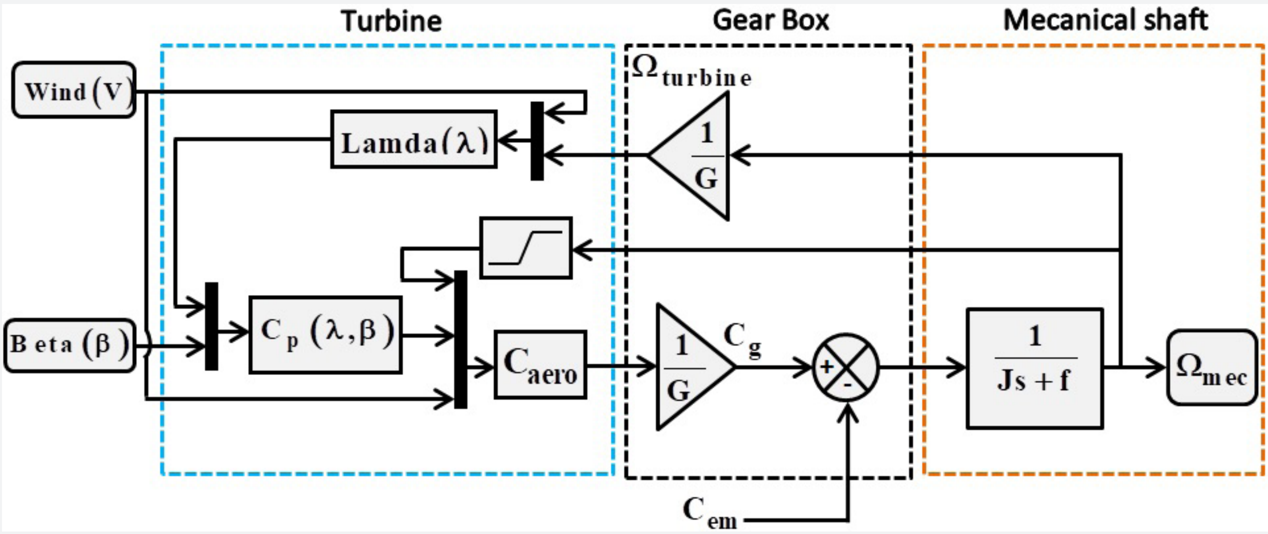

Figure 2: Functional modeling of the wind turbine [6].

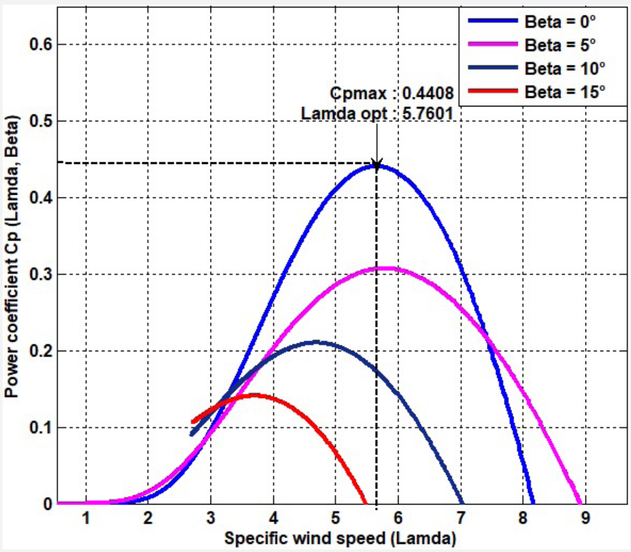

Figure 3: Caractéristique des performances (Cp) de la turbine eolienne.

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Table 1: Simulation parameters for turbine [2,11,12].

Turbine	
Parameters	Values
Pole pairs	P = 2
Gear box ratio	G = 90
Inertial of turbine	$J_{turbine}$ = 50. 105Kg.m2
Leakage coefficient	f = 0.03 (friction f)
Inertial of rotor	J_{rotor} = 682. 3Kg.m2
Rated power coefficient	Cp = 0.44
Nominal power of	2MW

MPPT regulations of wind turbine mechanical energy

The objective of the regulation for the MPPT of the wind turbine, is to allow the extraction of the maximum power from the kinetic energy of the incident wind thanks to the automatic and permanent adjustment of the mechanical speed of the aerogenerator. To do this, two control strategies such as the MPPT without and with speed control are studied in order to choose a more efficient control of the rotation speed corresponding to the optimal operation of the wind turbine, for values such as, $C_{p\max}$ = 0.4408, s λ_{opt} = 5.7601, β = 0°, and at any wind speed.

Synthesis of MPPT control without speed control

The regulation synthesis for MPPT without mechanical speed control consists of the estimation of the quantities that characterize an optimal operating state of the considered wind turbine. Therefore, assuming that the wind speed changes very little in steady state against the electrical time constants of the wind turbine, we can from Equation 6 write the following expression [5]:

$$\frac{d\Omega_{mec}}{dt} = C_{torques} = (C_g - C_{em} - C_{Vis}) = 0 \quad (11)$$

This amounts to saying that the sum of the torques $(C_{torques})$ developed by the turbine is considered to be zero. Moreover, if we neglect the viscous friction torque $(C_{Vis} = 0)$ in front of the electromagnetic torque (C_{em}), we can write [8,2]:

$$C_g = C_{em} \quad (12)$$

The rotational speed of the turbine $(\Omega_{turbine})$, can be determined from the measurement of the mechanical speed (Ω_{mec}), by the following expression:

$$\Omega_{turbine} = \frac{\Omega_{mec}}{G} \quad (13)$$

Whereas the estimate of the wind speed V_{est}, as a function of the optimum specific speed λ_{opt}, of the radius (R) and of the speed of the turbine is given by the relation:

$$V_{est} = \frac{\Omega_{turbine} R}{\lambda_{opt}} \quad (14)$$

The rearrangement of Equations (13), (14), with the maximum power coefficient $C_{p\max}$, makes it possible to determine the expression of the reference mechanical torque (C_{aero_ref}) of the turbine as follows:

$$C_{aero\_ref} = \frac{1}{2} C_{P\max} \rho \pi R^2 V_{est}^3 \frac{1}{\Omega_{turbine}} \quad (15)$$

The estimate of the reference electromechanical torque (C_{em_ref}) or control quantity, is written:

$$C_{em\_ref} = \frac{C_{aero\_ref}}{G} \quad (16)$$

Accordingly, the device of the MPPT control strategy composed of Equations (13), (14), (15) and (16), is associated with the model of Figure 2 to form the complete model of the wind turbine shown in the Figure 4.

MPPT control with speed control

The principle of the MPPT control strategy with speed control aims to automatically adjust the electromagnetic torque in such a way that the evolution of the rotational speed (Ω_{mec}) conforms to the shape of a speed of given setpoint (Ω_{mec_ref}), and thus considering the mechanical torque (C_g) as a disturbance. To do this, in the case of a study like this, the MPPT controller consists of Equation (14) for the estimation of the reference rotational speed of the turbine, Equation (13) for calculating the reference mechanical speed, and the transfer

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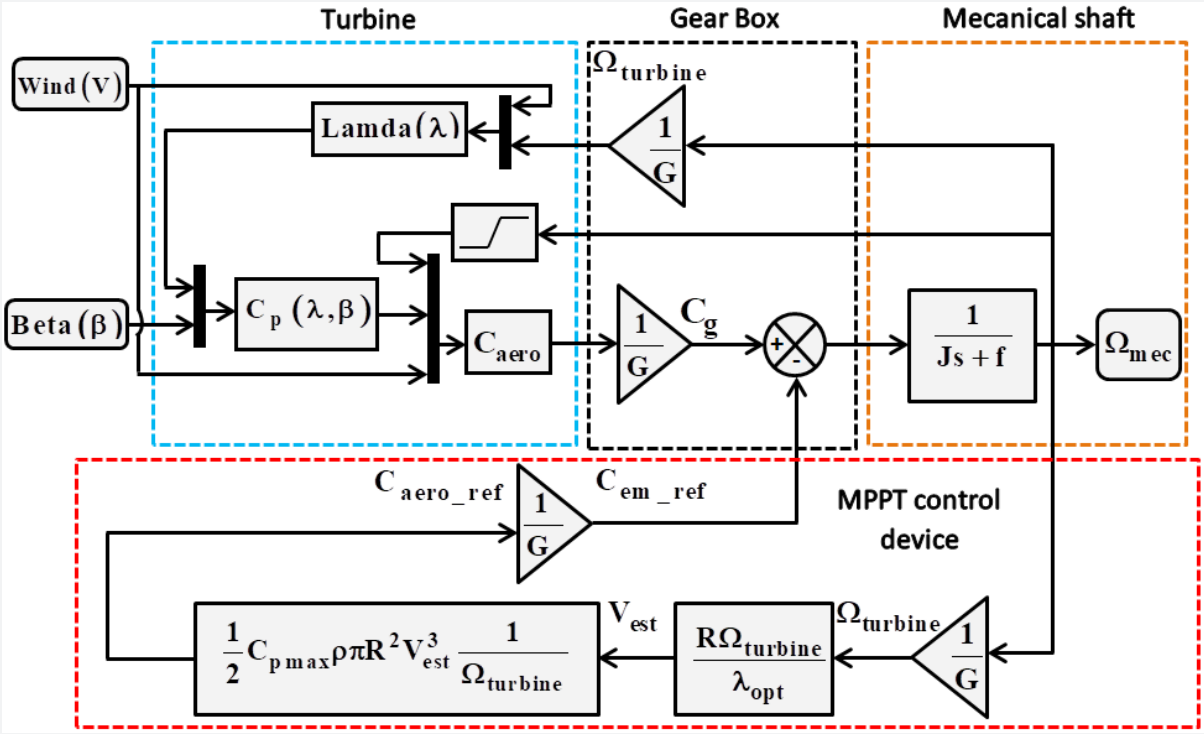

Figure 4: MPPT without mechanical wind turbine speed control [6].

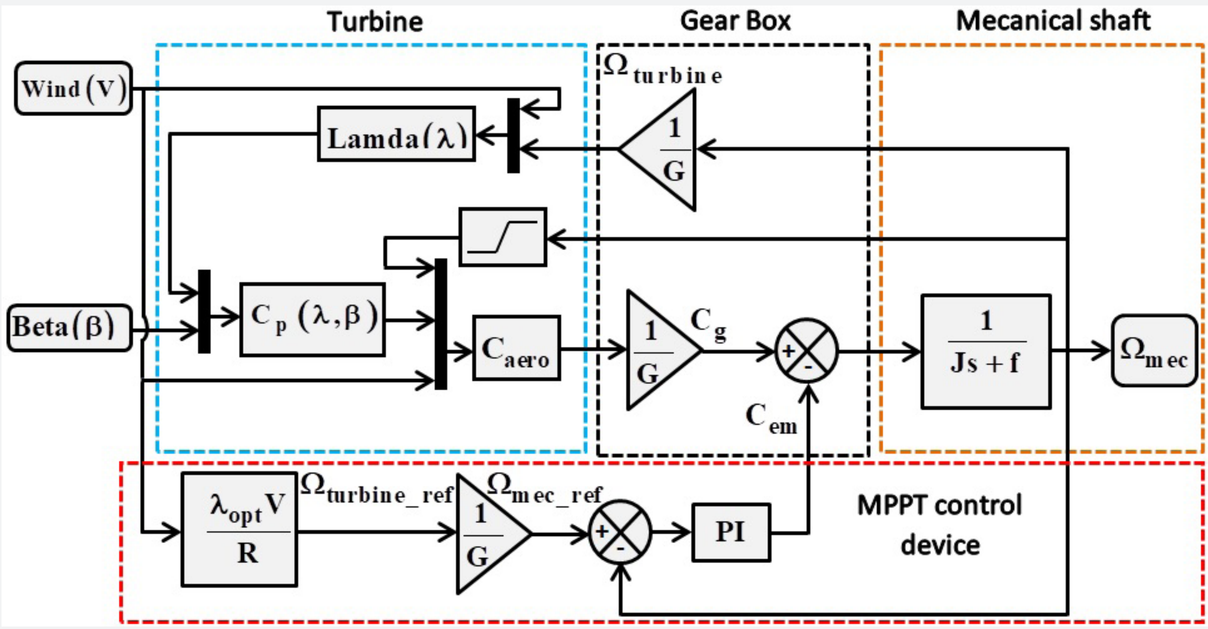

Figure 5: MPPT with PI control of the mechanical speed of the wind turbine [12].

function of the proportional integral (PI) regulator. All this is associated with the model of Figure 2, to obtain the simulation model of the wind turbine in the Figure 5.

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Synthesis of the PI regulator for MPPT with speed control

The sizing of the PI controller for MPPT with rotation speed control, can be formulated according to the principle of the regulation synthesis given in Figure 6. The latter will allow us to establish a relationship between the function of the corrector C(s) of the PI and the transfer function of the model of the mechanical shaft G(s), in order to determine the values of the coefficients KP and KI which will allow the PI corrector to regulate the mechanical speed.

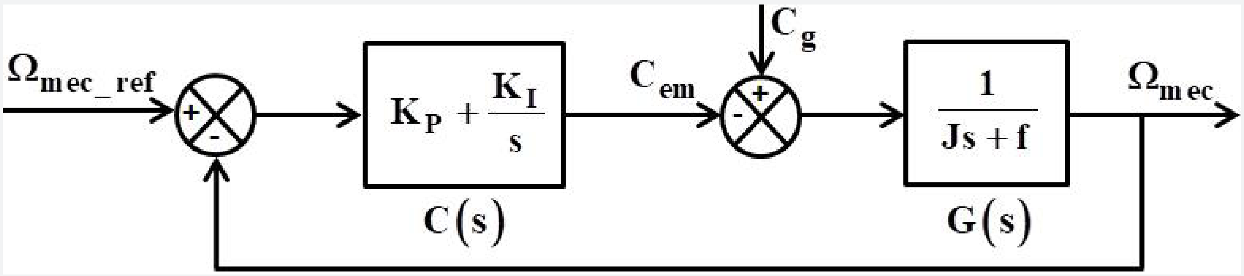

Figure 6: Principle of MPPT regulation with PI control.

To do this, the determination of the Closed Loop Transfer Function (FTBF) of the Figure 6, gives us the following Expression [4,12]:

$$FTBF_{mec} = \frac{\left(\frac{K_p}{J}s + \frac{K_I}{J}\right)}{(s^2 + [(f + K_p)/J]s + K_I/J} \quad (17)$$

By identifying the $TFBF_{\Omega mec}$ with a transfer function of a 2nd order filter, we deduce the following expressions:

$$\begin{cases} K_I = \omega_0^2 J \\ K_p = 2\xi\omega_0 J - f \end{cases} \quad (18)$$

The response time is given by the following Expression [4,12]:

$$\tau_r(n) = \frac{1}{\xi\omega_0}\left(\frac{100}{n}\right) \quad (19)$$

In our case study, we took n = 2, i.e., 2% and ξ = 1, in order to match a response time value that is fast enough for the GADA.

n: Actual value of the depreciation rate; ξ: Damping rate (unitless).

ω0: Filter cutoff pulse.

The numerical application of Equation 18 & 19 gives us for a response time constant τr = 40ms, the following proportional and integral gain values: kp = 136460, and kI = 6823000.

Results and discussion of MPPT simulations without and with speed control

To effectively evaluate MPPT commands models for Figure 4 & 5, two comparative case studies between the MPPT control without speed control and that of the MPPT with mechanical speed control are proposed from the simulation results obtained in the MATLAB/Simulink environment. For this purpose, two types of wind profile are used to translate the random behavior of the wind that a wind turbine could face in reality. In addition, the simulation parameters of the 2MW wind turbine used are given in Table 1 in appendix [5, 12], and the setting angle is fixed at β = 0° in order to always hope for operation of the wind turbine close to optimal conditions whatever the nature of the uncertainties.

1st simulation case of the comparative study of MPPTs

In this case study, the wind profile defined in Figure 7 reflects the nominal wind speed regime V = 11.2m/s in the time intervals (0s to 20s) and (40s to 60s); as well as the states of sudden wind changes at times t = 0s, 20s and 40s. Overall, the simulation results show us that the values of the quantities $C_{p\max}$, λ_{opt}, Ω_{mec} and P_{aero} shown in the Figure 8(a),8(b) and 11(a),11(b) are almost identical for the two MPPT strategies studied. Similarly, these values obtained on the curves of Figures 8-11 are also close to the nominal values of the wind turbine in the study, namely $C_{p\max}$ = 0.4408, λ_{opt} = 5.7601, Ω_{mec} = 144 rad/s and P_{aero} = 2MW. However, Figures 8-11 also show that the curves of the two MPPT strategies are more sensitive to the sudden decrease in wind at

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time 20s, compared to the sudden increase in wind at time 40s. Moreover, in Figures 8(b)-11(b) the shapes of the curves of the MPPT strategy using the PI are stable and converge more quickly than the curves of the Figures 8(a)-11(a). Because, at times 0s, 20s and 40s of the Figures 8-11 the influences due to sudden changes in the wind lead to transiently visible reactions (great slowness and disturbances) in the Figures 8(a)-11(a) of the MPPT controller without PI, unlike the MPPT controller with PI, whose curves in the Figures 8(b)-11(b) react more impulsively (faster and less disturbed).

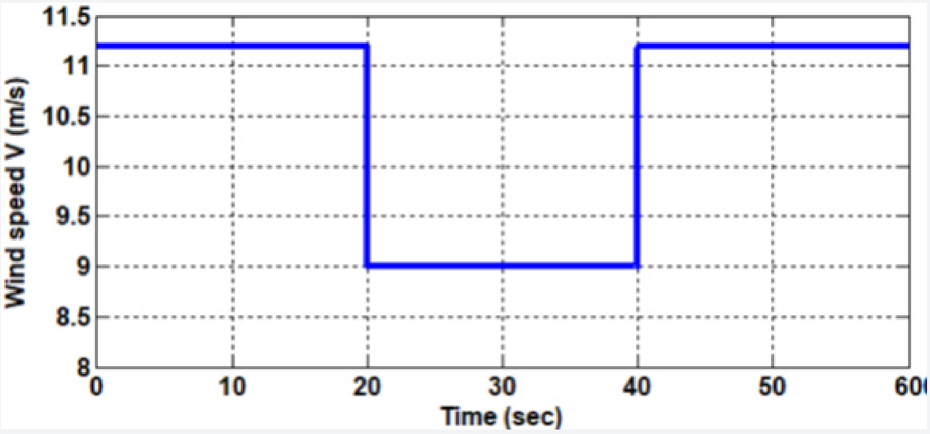
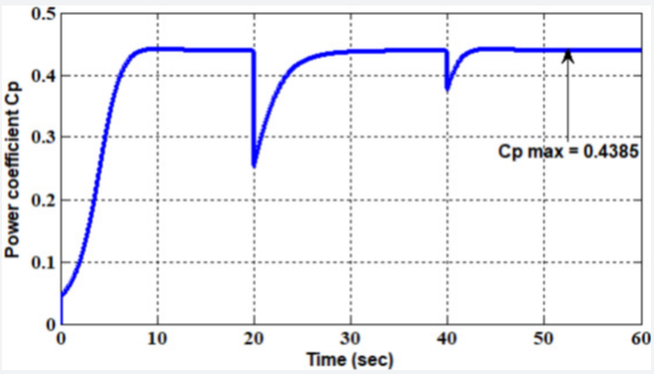
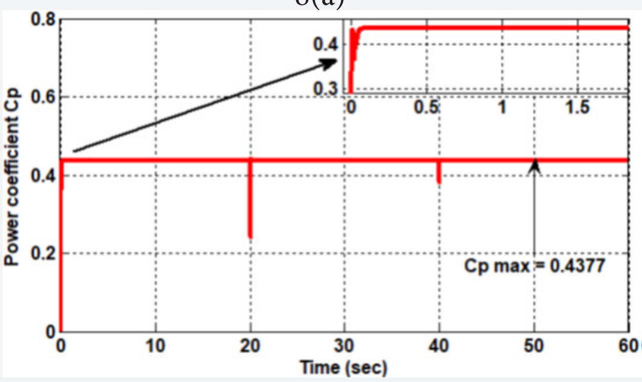


Figure 7: Permanent and abruptly changing wind profile.



8(a)



8(b)

Figure 8: Maximum power coefficients of the MPPT without speed control (a) and with speed control (b) for non-random wind.

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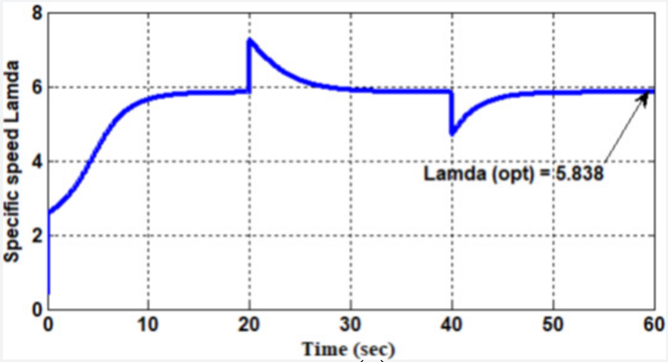
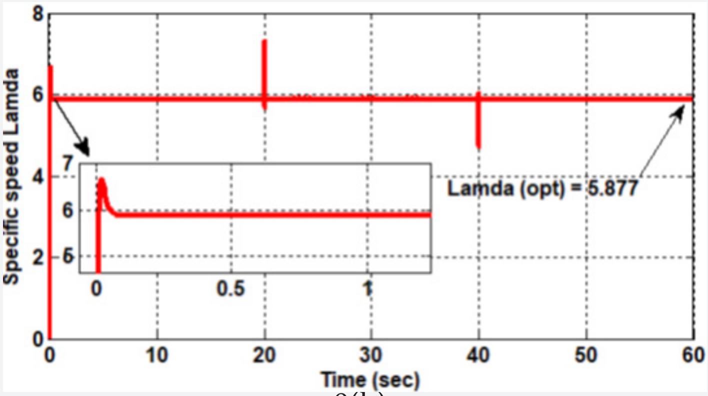
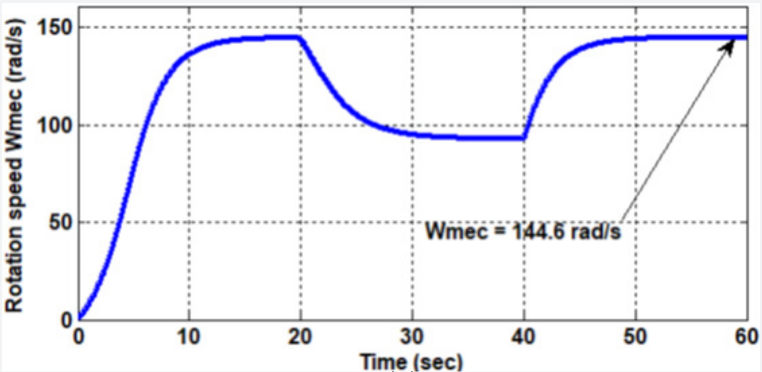


9(a)

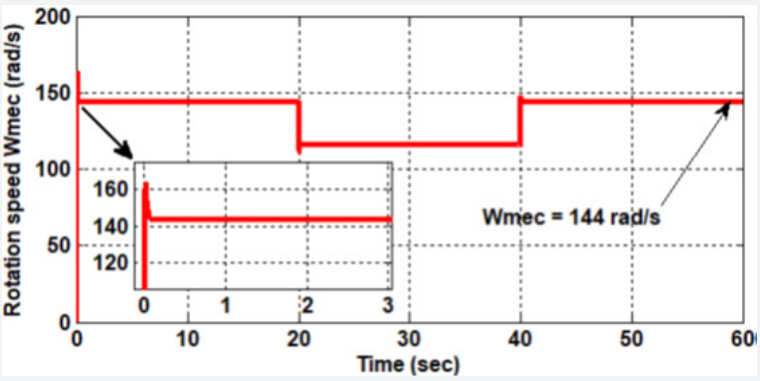


9(b)

Figure 9: Optimum specific speeds of the MPPT without speed control (a) and with speed control (b) for non-random wind.



10(a)



10(b)

Figure 10: MPPT rotation speeds without speed control (a) and with speed control (b) for non-random wind profile.

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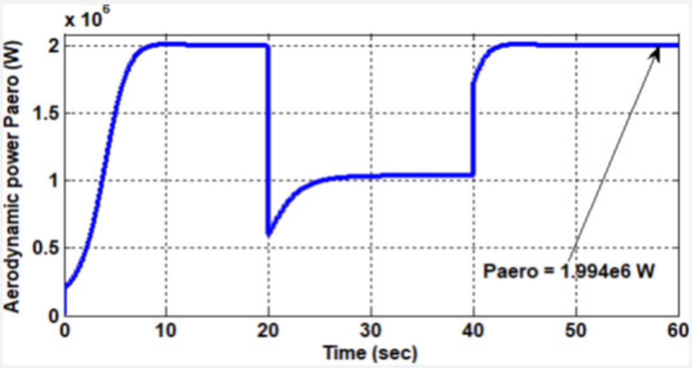
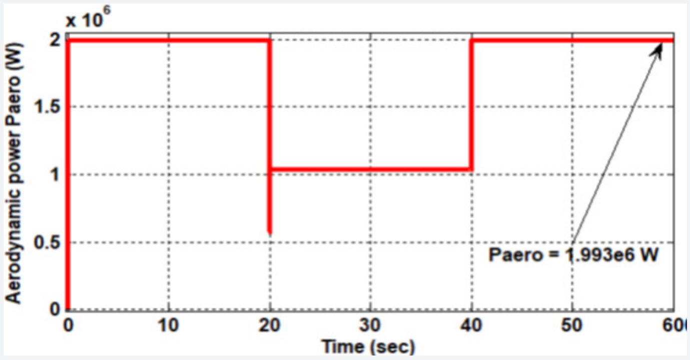


10(a)



10(b)

Figure 11: Aerodynamic powers of MPPT without speed control (a) and with speed control (b) for non-random wind profile.

2nd simulation case of the comparative study of MPPTs

The wind model usually used to approximate the real wind conditions, is often given by the following Expression [12]:

$$V = 11.4 + ((0.2\sin(0.1047t) + 0.2\sin(0.2665t) + 0.2\sin(3.6645t)) \quad (20)$$

The model simulation of equation (20) gives us the wind profile shown in Figure 12.

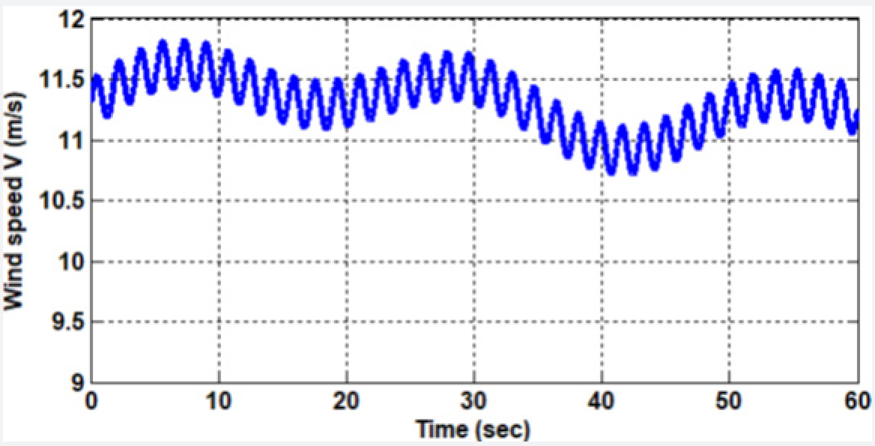


Figure 12: Random wind profile.

The MPPT simulation results with the random wind profile in the Figure 12, give us the curves illustrated in the Figures 13-16 from which it can be observed in steady state that the curves of the MPPT strategy without speed control have performances close to the curves of MPPT with speed control. In addition, the shapes of the curves of Figures 13-16 for the two MPPT strategies studied follow well the behavior of the wind model of Figure 12. However, by carefully observing the Figures 13-16 it is also noted

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that the curves of the quantities C_p, λ, Ω_{mec} and P_{aero} of the MPPT strategy with PI, converge faster and are more stable than the curves of the MPPT controller without speed control. Indeed, the latter presents on all its curves not only a great slowness, but also loss of information. In addition, the MPPT curves without PI show a high sensitivity to disturbances compared to the MPPT curves with PI. Nevertheless, the overruns are more visible at the start on the curves of Figures 13-16 of the MPPT strategy with speed control. In short, it emerges from all these two case studies that the MPPT strategy with speed control has the advantage over the MPPT control without speed control, in particular with regard to the performance of speed, precision, and speed. stability that will help reduce problems related to mechanical stresses on the wind turbine shaft. In addition, the MPPT strategy with speed control is better suited for the development of more advanced controllers for quantity and quality energy production which will increasingly meet the requirements of manufacturers.

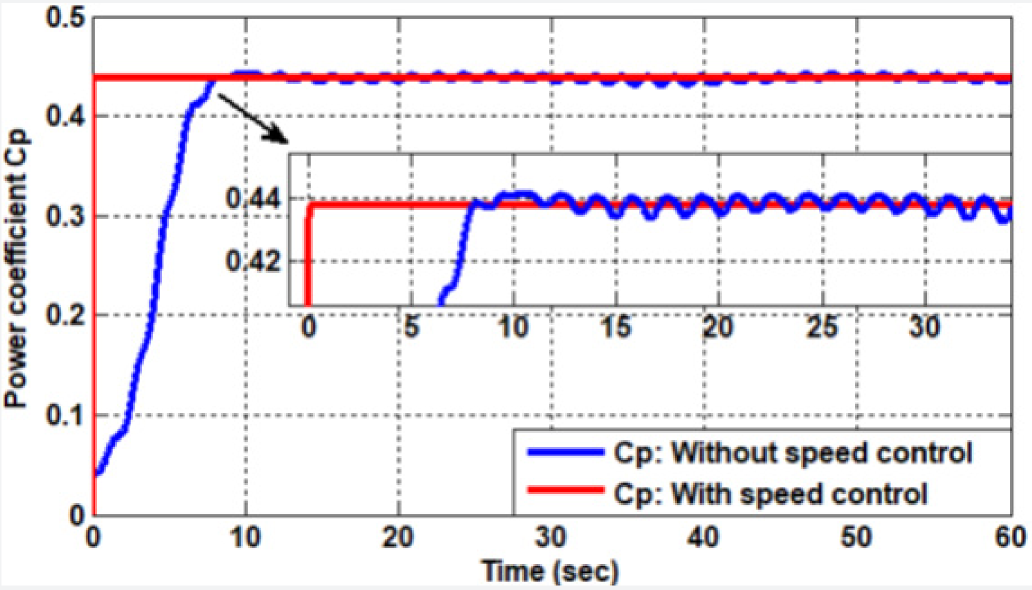

Figure 13: Maximum power coefficients of two MPPTs studied for random wind.

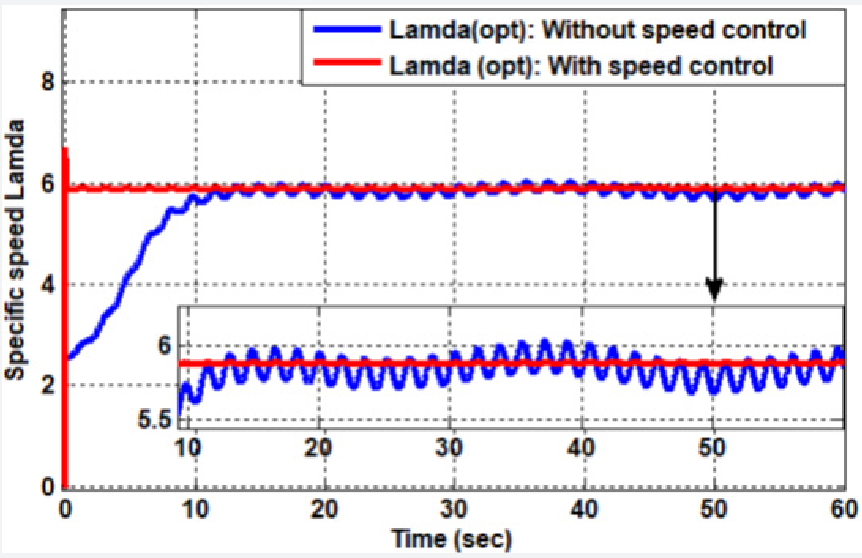

Figure 14: Optimal specific velocities of two MPPTs studied for random wind

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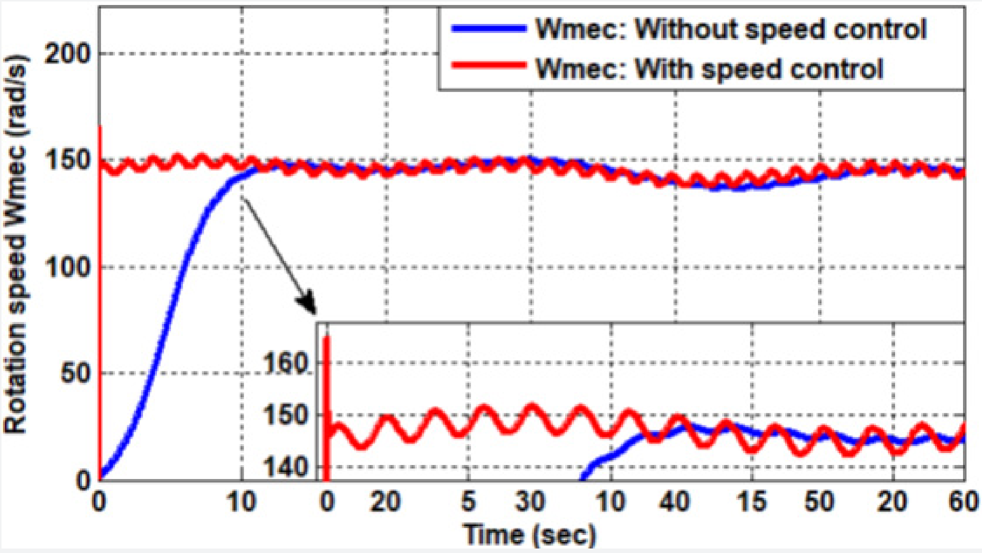

Figure 15: Rotation speeds of two MPPT studied for random wind

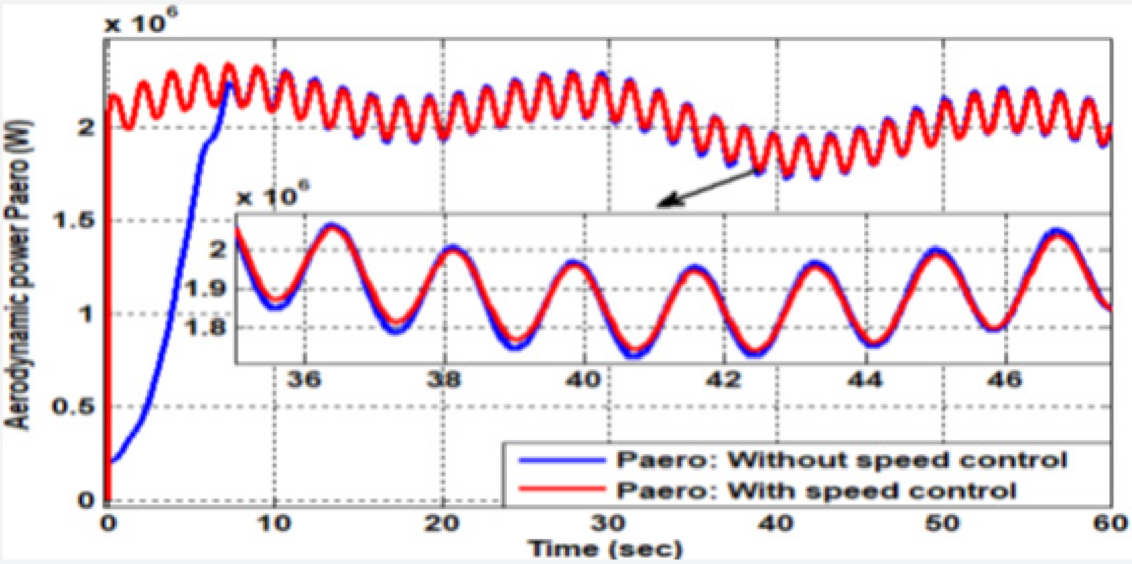

Figure 16: Aerodynamic powers of two MPPTs studied for random wind

Conclusion

It was a question in this work of proposing an approach aiming at the choice of an adequate control structure for the regulation of Maximum Power Point Tracking (MPPT) of wind turbines. This consists of evaluating the static and dynamic performance of wind turbines in accordance with the predictive requirements of manufacturers. Also, given the unpredictable behavior of the wind, the targeted strategy makes it possible to guarantee the wind turbines a production of energy in quantity and quality, making it possible, among other things, to reduce mechanical wear on the aerogenerators. To do this, a characteristic model of the 2MW wind turbine, and a comparative study between two MPPT structures with and without speed control, were presented. The results of this approach show that, for different wind conditions, the MPPT strategy with speed control has the advantage over the MPPT control without speed control. Because, with regard to the performance of speed, precision and stability, the strategy of MPPT with speed control is best suited for the development of increasingly advanced and efficient controllers to meet the requirements of real operating conditions. of the aerogenerator.

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