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AERODYNAMIC PERFORMANCE ANALYSIS OF SMALL WIND TURBINE BLADES USING NREL S809 PROFILE AND VARIOUS TIP SPEED RATIOS

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Abstract: *One of the main factors that influence the operation and efficiency of wind generators is the aerodynamic performance. Therefore, the rotor blades are the primary target of this study. They are the aerodynamic components that interact directly with the air flow for the transformation of kinetic energy of the wind into electrical energy. This work proposes the design, build and testing the blades of a small wind turbine. The rotor was built with 3.0 m diameter, equipped with three blades using the airfoil NREL S809 profile. The blades were developed according to the BEM (Blade Element Momentum) theory, resulting in geometry of maximum aerodynamic performance. Four distinct sets of blades were used in the performance tests; they differ from each other by the value of the tip speed ratio. The values applied were equal to 6, 7, 8 and 9. In the tests, it was found a little dependence on the measured torque as a function of the specific speed operation, which is a characteristic of the high-speed wind turbines. The test results reveals that the blade with tip speed ratio 7 showed the best average performance, obtaining a maximum coefficient of performance equal to 31%.*

Keywords: *wind turbine, tip speed ratio, field tests, coefficient of performance*

1. INTRODUCTION

The increasing awareness from general public about climate changes and global warming let the man looking for alternatives energetics sources that assure a sustainable future. In general way, there is a consciousness that the world needs a new energetic paradigm, since the energy sources used in 20th century, for instance oil and natural gas, have not renewable characteristic. There are studies that affirm that the fossil energy reserves will be depleted in the next 30 years. (Quaschining, 2005).

On the contrary way, there was a substantial increasing demand for energy. Therefore, a solution is needed to the problem that can occur in the global energy matrix. In this context, nowadays, the pursuit for alternatives sources of energy has increased considerably. Many renewable resources are been explored: the wind power, hydropower, solar energy and biomass.

The use of abundant and clean energy source such as wind has provided the opportunity for solving energy problems which resulted in improving in the capacity installed global. The Figure 1 shows the global cumulative wind capacity installed from 1996 to 2012 (GWEC, 2013).

As shown, the production of electrical energy through the wind energy is increasing. The technological development has provided bases for it. Companies and research groups around the world are trying to get ways to make the process of converting wind energy to other kind of electrical energy more efficient.

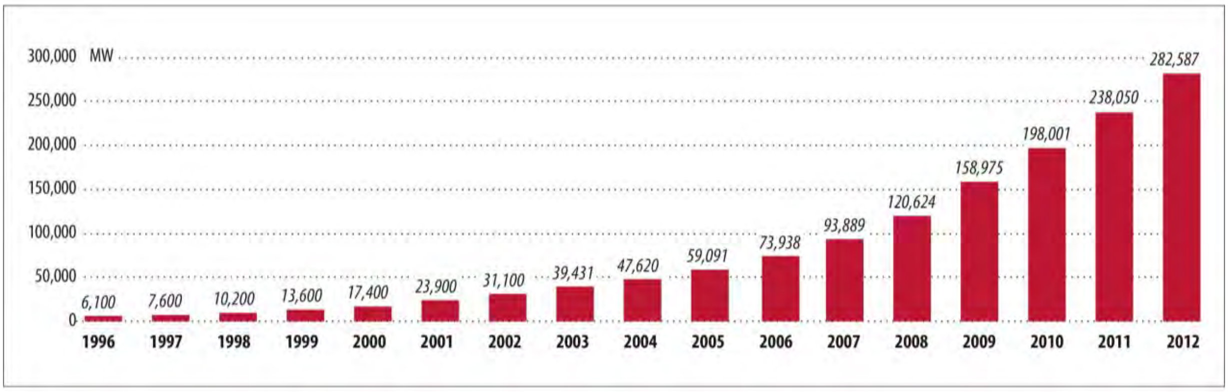

Figure 1. The global cumulative installed wind capacity from 1996 to 2012 (GWEC, 2013)

Concerning to the feasibility of a wind turbine, one of the mainly factors in its design analysis is the studying of its power curve. Which consists in power coefficient against tip speed ratio chart (C_p x λ), the former is the ratio between mechanical power from the shaft and wind power (kinetics energy flow), and the latter is the specific speed in the blade tip. (Rocha *et al.*, 2010)

In this paper, field tests were performed with a model of small wind turbines tested in low Reynolds conditions. This is typical of rural, suburban and even in the populated city areas where installation of large scale wind turbines would not be accepted due to space constraints and generation of noise. The small wind turbines are vital wind power extracting in this situations (Singh and Ahmed, 2013).

2. METHODOLOGY

2.1 Rotor Blade Design

The design of the rotor requires aerodynamic theory for designing, because its blades are composed of alar profiles which are aerodynamics body with complex geometry. Extensive calculations are needed to determine parameters such as chord (c), the profile thickness and distribution of twist (β) along the length of the blade.

The first step to design the rotor é assume which it works is an actuator disk (Burton *et al.*, 2001) utilizes to absorb some of the kinetic energy, converting it to mechanical power shaft. The interference is divided into an axial component and a tangential described by their respective factors: axial interference factor (a), which is the fraction of the axial velocity that the fluid lost by passing through the turbine, and the tangential interference factor (a'), which is the fraction of the speed of rotation of the rotor is transferred to the fluid in the form of angular momentum (Rocha, *et al.* 2010).

Betz (1926) determined the optimal value of the axial interference value (a = 1/3) resulting in the maximum efficiency of a wind turbine (53.9 %). Efficiency is measured by power coefficient (C_p) is defined as the ratio between the shaft power and the flow kinetic energy passing through the rotor:

$$C_p = \frac{P_{shaft}}{FEC} = \frac{\omega.T}{\frac{1}{2}\rho A U_\infty{}^3} \quad (1)$$

The next step in the rotor is to determine the geometry of blades. The blade element momentum theory (BEM) (Burton *et al.*, 2001) is used to obtain the geometry with maximum efficiency for a wind turbine. This theory calculates the angles of twist according to the profile and taper. It is assumed that the forces on the blades of a wind turbine can be expressed as a function of lift and drag coefficients, and its result is responsible for the change in momentum. For this analysis, the rotor blade is divided into *N* sections and following assumptions are made (Manwell *et al.*, 2005):

1) There is no interaction between the aerodynamic elements (no radial flow);
2) The forces on the blades are determined solely by the lift and drag characteristics of the airfoil blade.

This theory admits two-dimensional flow over the blades, that is, the radial component of velocity is ignored. This condition is satisfied if the axial interference factor does not vary radially. For each radial position, the relative velocity (W) can be determined as a result between the wind speed $[U_\infty\,(1-a)]$ and the rotation speed of the rotor$[\Omega\, r\,(1+a')]$ (Manwell *et al.*, 2005). The Figure 2 shows the speed components in an element of blade.

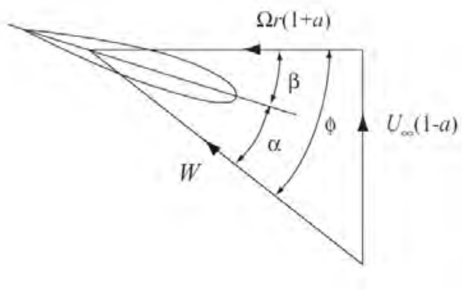

Figure 2. Angles in the element of blade (Burton *et al*., 2001)

At Figure 2 is showed three angles which will be utilized in blade design: α is attack angle, β is twist angle and ϕ is the angle of incidence of the wind on the blade.

The geometry of the rotor is then fully defined by two parameters: the chord (c) of each blade radial position and the angle of incidence of the wind on the blade (ϕ) defined in Eq. (2) and Eq. (3), respectively (Manwell *et al*., 2005).

$$\phi = arctan\left(\frac{2}{3\lambda_r}\right) \quad (2)$$

$$c = \frac{8\pi rsen\,\phi}{3BC_l\ \lambda_r} \quad (3)$$

Where λ_r is the local speed ratio which is function of the tip speed ratio (λ) (Manwell *et al*., 2005) :

$$\lambda_r = \lambda\frac{r}{R} \quad (4)$$

The twist angle (β) is obtained by the following expression (Manwell *et al*., 2005)

$$\beta = \phi - \alpha \quad (5)$$

The attack angle (α) is fixed in the value which corresponding to the maximum ratio $C_L\ /\ C_D$. How the profile used was NREL S809 (see Figure 3), we utilized $\alpha = 6.11°$ which corresponding to $C_L = 0.748$.These values are obtained for $Re = 3 \cdot 10^5$(Butterfield *et al*., 1992).

The rotors are made up of three blades, which are of the same length 1.5 meters and NREL S809 Profile. Four distinct sets of blades are used in the tests. They differed from each other by the value of the speed ratio tip design, with values equal to six, seven, eight and nine.

The blade geometry obtained from BEM theory equations for project tip speed ratio (λ) values are described by the dependence of the profile chord and twist angle as a function of the size radially along the blade. The Figure 4 shows the curves of tapering and twisting of the blades used in the tests.

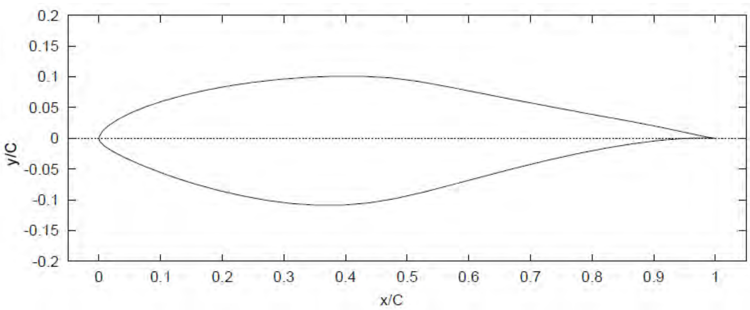

Figure 3. Profile NREL S809 (Leishman *et al*., 2006)

The graphs (a) and (b) from Figure 4 show which there is a gradual decrease of twist and chord profiles used along the length of the blade. This ensures that in operation regime variable has a higher efficiency in energy extraction. Expected efficiency of each blade when it is operating at λ designed.

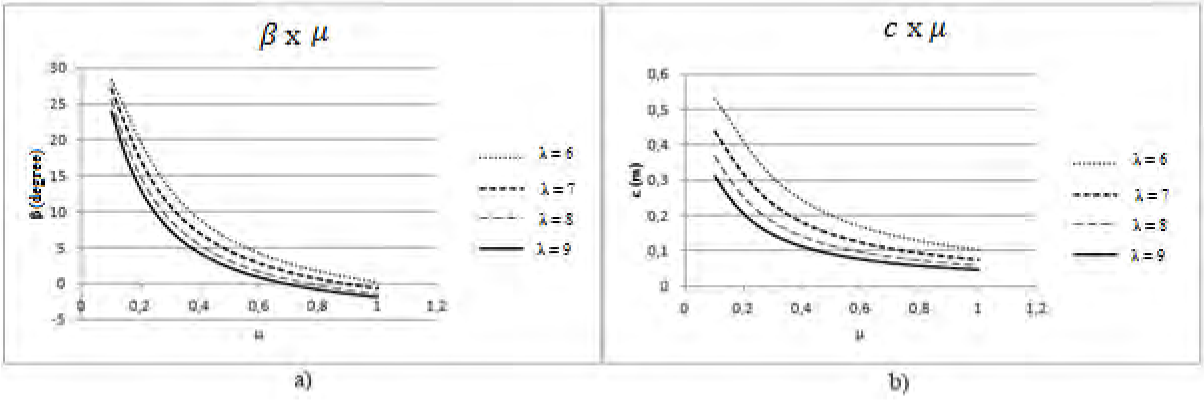

Figure 4.The caption for the data symbols as well as the labels for each curve

All blades were divided into 20 sections (N = 20). The sections of the profiles 19 with their chord were generated in CAD software, printed on a 1:1 scale, glued on balsa wood of 3/16 ", cut and polished for finishing. Aluminum Stringer was used to position profiles. Subsequently profiles were glued with its twist from designed on stringer and covered with balsa wood 1/16 "(see Figure 5).

Figure 5. Blade assembly

After the complete encasing blade, its surface was painted with epoxy and fiberglass to provide greater resistance and stiffness blade structure.

2.2 Field tests

One purpose of this study was to collect data from aerodynamic performance of wind rotors. The nacelle (Figure 6) is formed by a base containing a shaft, a brake drum, two mandible type couplings, one torque transducer, one tachometer with inductive sensor and one sonic anemometer, which simultaneously measured the wind speed, allowing obtain data for the curves $C_p\ x\ \lambda$, $Torque$ x λ e P x λ.

Figure 6. Measurement base

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Characteristics of the instruments used:

1) Torque transducer: for the acquisition of values of torque was used a transducer which work like a strain gage operating with angular position inductive system capable of measuring torque on a shaft under static and dynamic conditions. The model used was the HBM T22. The technical specifications in accordance with the manufacturer are: Reading Range 200N.m up with error and rotation rate 9000 rpm limit. It has power source 30 V to 11.5 V and the analog output signal from 0 to 5 V.

2) Tachometer: for the acquisition of values of rotation of the blades, we used a digital tachometer model TS-TADIG, with inductive sensor which is based on operating one-way microcontroller pulse counter. The instrument operates in the range of 4MHz to 5 V.

3) Anemometer: the values of wind speed were obtained with the use of ananemometerWindmastermodelPK-1590-020, which is based on the operation of the travel time of the emission of ultrasonic pulses for transducers with parallel faces. For each pair of transducers speed is measured in one direction. Therefore, as the instrument has three pairs of transducers are measured velocities in the three Cartesian directions (x, y, and z).

4) Data acquisition system: how signals obtained by the measuring instruments use dare all analogical, it was necessary to converter the signal captured. For this, we were used a data acquisition system consists of a computer, a data loggerEnviroMonEL005 model and two converters EnviroMon EL037.

The Figure 7 shows the assembly of the experimental apparatus. The experimental tests were conducted in an area belonging to the Department of Agricultural Engineering (DENA) from UFC.

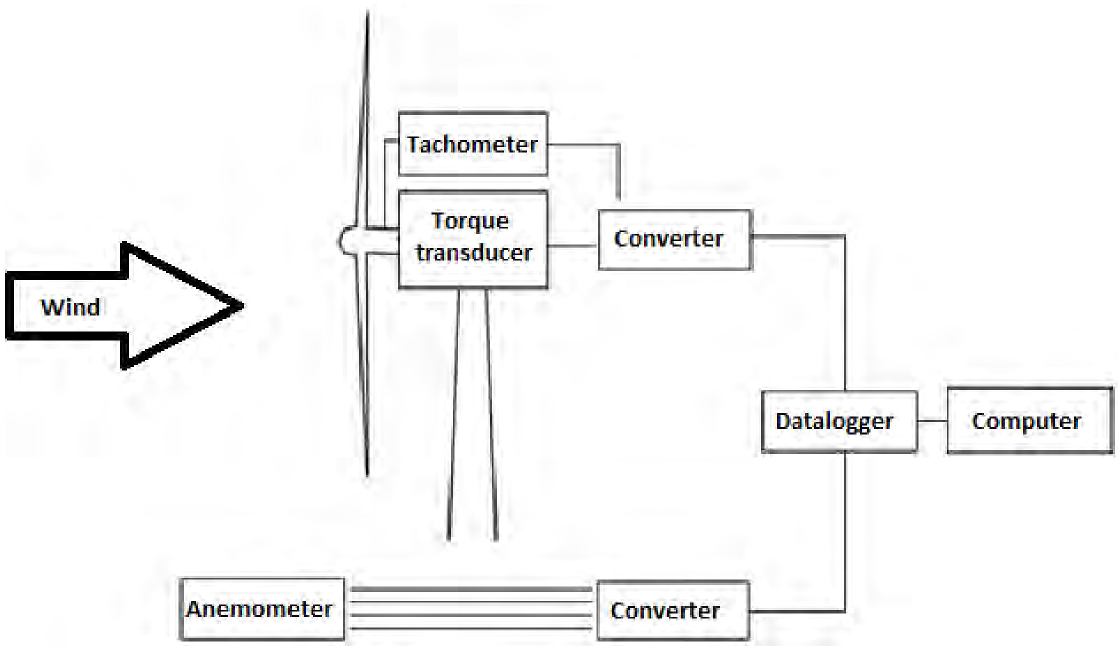

Figure 7.Experimental apparatus

A guyed tower modular type with 5m in height was used to arrange the rotor at a height to make the measurements. We also used a rudder to guide the rotor shaft with the wind direction, being stuck in the back of the nacelle, Figure 8.

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Figure 8. Guyed tower, rudder, nacelle and rotor

3. RESULTS AND DISCUSSION

3.1 Wind speed

Tests were performed on different days totaling the ideal period to make the desired measurements 100 for each set of blades. The measurements included torque, power and speed values. The characteristics of the wind regime in the days of the tests are shown in Table 1.

Table 1. Wind characteristics.

$\lambda = 6$	$\lambda = 7$	$\lambda = 8$	$\lambda = 9$
Average speed	Average speed	Average speed	Average speed
2.9849	3.8211	2.6749	3.3678
Standard deviation	Standard deviation	Standard deviation	Standard deviation
1.1923	2.9644	0.7535	0.8221

3.2 Peformance curves

During the tests, the the wind speed varied, many values of λ were Obtained including λ_d. The Figure 9 shows the 100 measurements of C_p with its value of λ for the rotors tested.

For processing of the data, the points were divided at intervals of λ values, obtaining the mean value of each variable in the interval examined. The error range was evaluated based on a Student's t distribution with 95% confidence and expressed by error bars. There was thus obtained the graphs of torque, power and potency coefficients with new values.

The torque was no significant variation in the values of λ obtained in the field for four pas tested (see Figure 9). The little variant of torque to the blades with different λ_d is a typical feature of high speed wind turbines. This is a desirable feature of high performance turbines because, since the torque is maintained, the increase in speed results in a higher power extracted.

The power extracted (see Figure 10) is obtained by multiplying the angular speed by torque. The power obtained increases in high rotation, but is limited by drag and blocking effects. The rotor acts like a solid disc at high rotation. In this situation, the air flows radially causing a reduction in lift. This was not expected effect and impedes the increase in speed.

The highest value of maximum power coefficient (C_{pmax}) was obtained in the testes of the rotor with λ_d = 7 blade. The C_{pmax} de 31% was achieved when λ operation approached project (λ_d) as expected. close to the project (see Figure 11).

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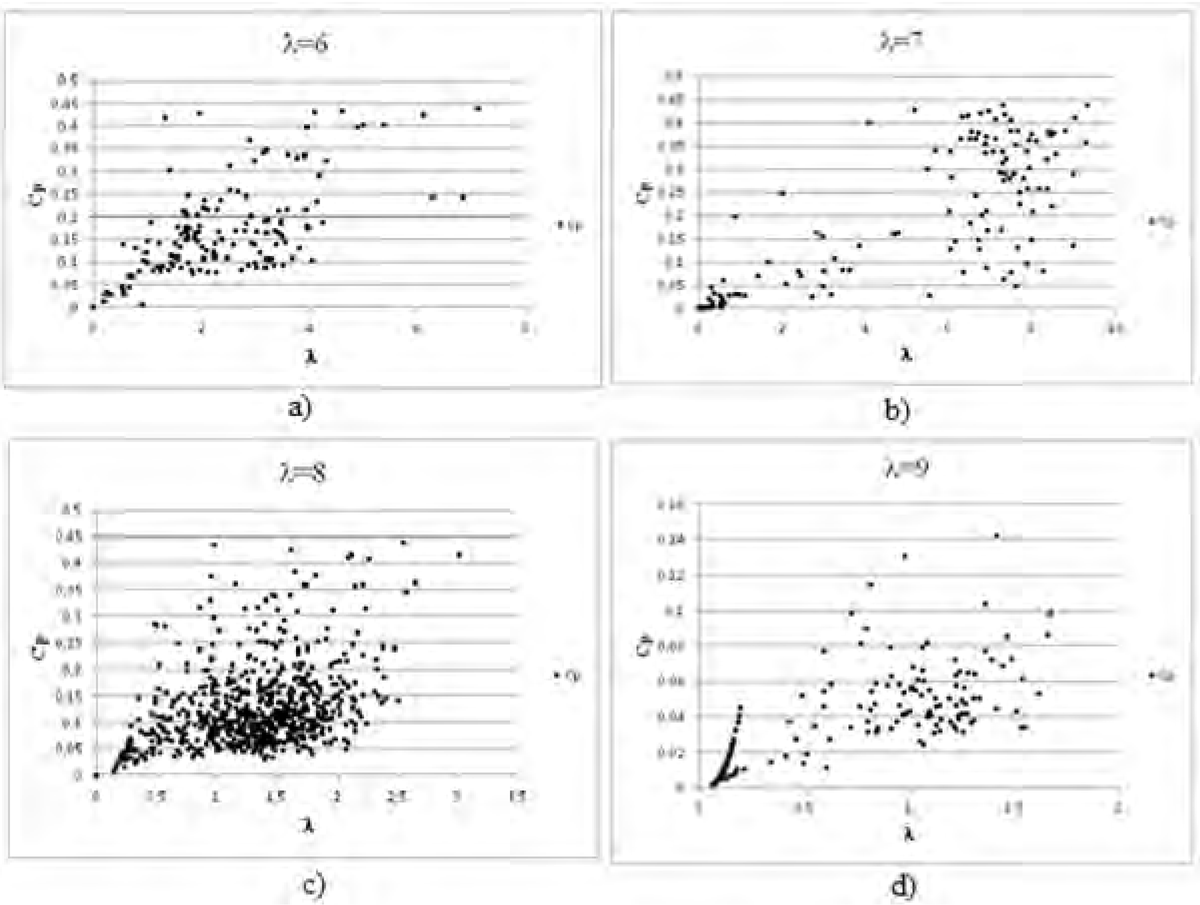

Figure 8. Point chart ($C_P\ x\ \lambda$)

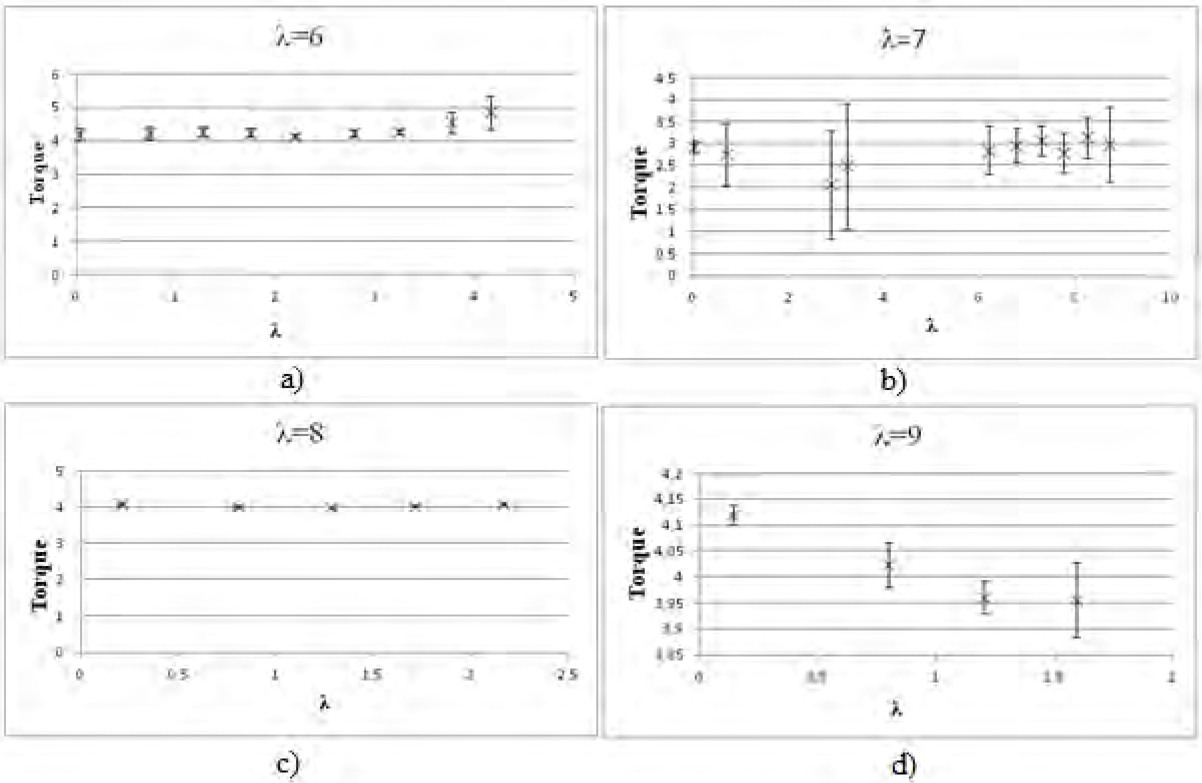

Figure 9. $Torque\ x\ \lambda$ curves.

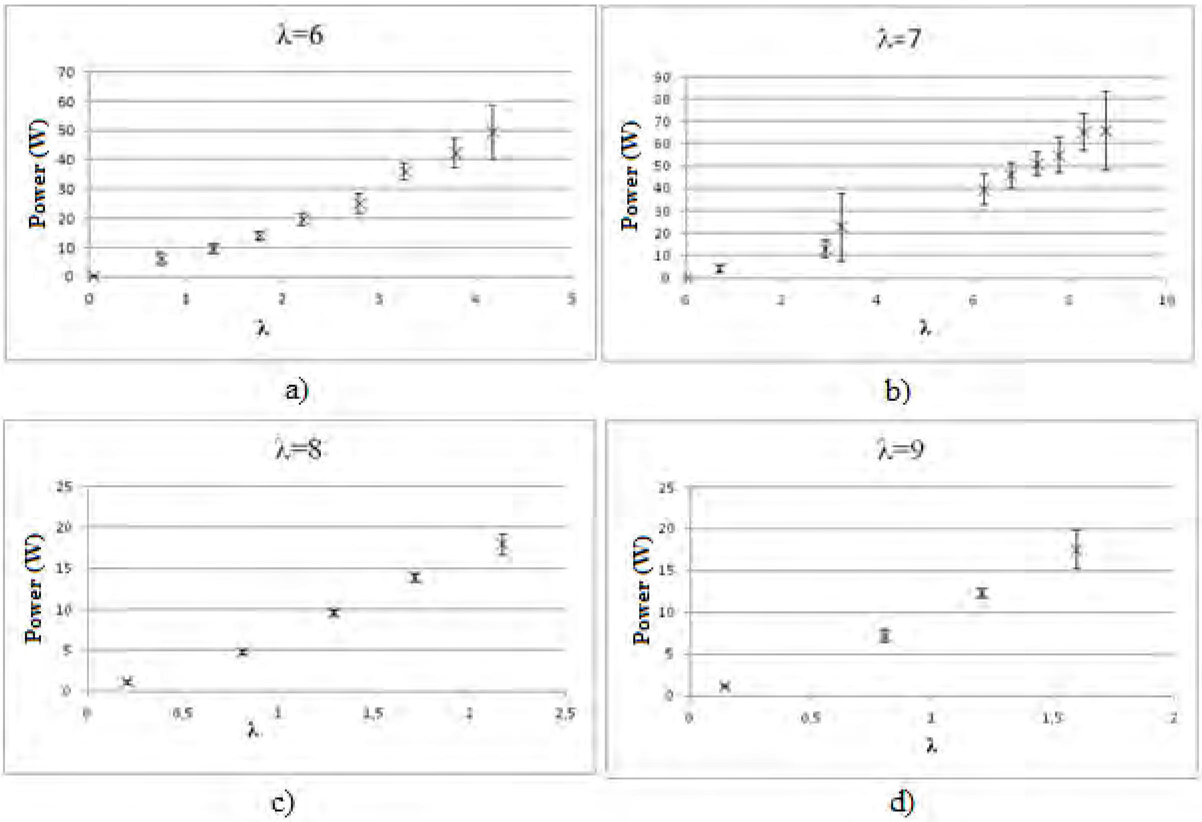

Figure 10. $Power\ x\ \lambda$ curves.

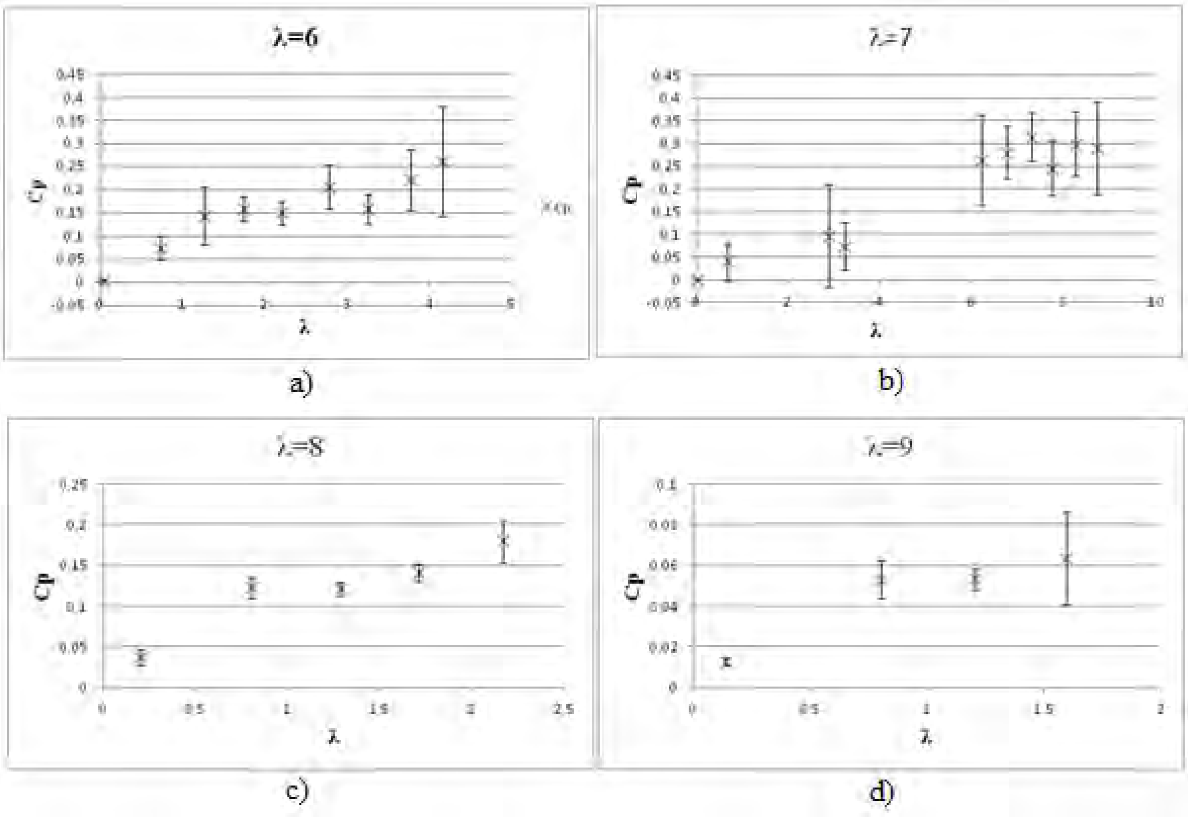

Figure 11. $C_P\ x\ \lambda$ curves.

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4. CONCLUSION

Four set of blade (with values of λ_d equal six, seven, eight and nine) were tested with low average wind speed (between 2.98 m/s and 3.82 m/s). In this situation is better to work with two rotors which have blades designed with lower values of λ_d (six and seven). These blades respond better with low speed wind because they have larger values of twist angles and chord which providing more lift in theirs profiles.

The field tests showed which the blade with $\lambda_d = 7$ had the best performance, obtaining a value of C_P maximum of 31%. This blade showed the best average performance within the system operating close to λ design compared, too.

However, in next test, we need to design blades with theory which predict blocking and drag effects because these impede the increase in rotation speed and, consequently, decrease the aerodynamic performance of wind turbine.

If it is possible to increase the rotation speed, the greater power extracted due the torque measured in the tests did not vary greatly in the different set blades. That is, the power extracted proved to be only function of the speed of rotation of the rotor.

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6. REFERENCES

Burton, T., D. Shape, N. Jenkins, and E. Bossanyi, 2001. *Wind Energy handbook.* John Wiley & Sons Ldt..

Butterfield, C. P., Musial, W. P., Scott, G. N., Simms, D.A., 1992. *NREL Combined Experimental Final Report - Phase II*. National Renewable Energy Laboratory. Colorado, United States.

GWEC, 2013. "Global Statistics". 1 Feb., 2013. < http://www.gwec.net/global-figures/graphs/>.

Leishman, J. G. (2006). *Principles of Helicopter Aerodynamics.* Cambridge University Press.

Manwell, J. F., McGowan, J. G, Rogers, A. L., 2006. *Wind Energy Explained – Theory, Design and Application.* John Wiley & Sons, Chichester, 2nd edition.

Quaschning, V., 2005. *Understanding Renewable Energy Systems.* London : Earthscan.

Rocha, P. C., Carneiro, F. O., Lopes, A. S., Maia, I. A., & Modolo, A. B., 2010. "Montagem e Testes de uma Bancada para Medição de Desempenho de Aerogeradores em Escala". *Revista Brasileira de Ensino de Física*, Vol. 32.

Singh, R.K., and Ahmed, M.R., 2013. "Blade Design and Performance testing of a small wind turbine rotor for low wind speed applications". *Renewable Energy,* Vol. 50, p. 812-819.

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