DESIGN OF A SMALL WIND TURBINE ADAPTED FOR WIND CONDITIONS OF SÃO TOMÉ

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Abstract. *The This paper presents a study about the design of a horizontal-axis wind turbine subject to wind regime of São Tomé, Maracanã, Pará State. In the wind rotor design will be use the Selig 1223 aerodynamic profile for slow Reynolds number, commonly used in model airplanes with the characteristic of high lift. The method to the construction of the wind rotor is the model developed by Vaz et al. (2010) with a modification. The results are compared with experimental data of a low-speed wind turbine available.*

Keywords: *Wind Turbines, Selig 1223, Wind Power.*

1. INTRODUCTION

Harnessing wind power is becoming increasingly important primarily for use in power generation demands facing small wind energy, which are common in isolated communities. In Brazil, given its continental size and the shape of occupation over time, the electricity service does not provide society as a whole. In the Amazon region where there are areas where there is poor provision of services, with fewer hours of care daily, usually between 4 and 12 hours, frequent interruptions and low quality of electricity, and other marks his reality, totally isolated, far from major centers and difficult to access, often located in tangles of rivers, which prevents the extension of conventional power grid. For this reason, the wind systems for small and medium-sized electricity generation are presented as an important form of renewable energy use in locations distant from major urban centers.

For the regions of the Amazon are common low wind speeds (Frade and Pinho, 2002b), where it is necessary to develop wind power systems more efficient. Measurements and estimates already made show good levels of wind speed at 50 m height on the coast of the states of Amapá, Pará and Maranhão and in the mountainous region of Roraima (Barbosa, 2006), justifying studies that are being developed in municipalities such as São Tomé, located in the municipality of Maracanã in Pará state, which has an average speed of wind around 4 m/s. In this case the horizontal axis wind turbines are the most widely used, as they usually have higher speed when compared to the vertical axis (Akwa and Petry, 2010). The aerodynamics of the blades have key role in calculating the power coefficient of the turbine, since the interaction of flow with the turbine causes the appearance of the lift and drag forces on the blades, which are responsible for the performance of the rotor. Thus, this work will be shown an alternative model for the wind rotor design, which will be an extension of the model developed by Vaz *et al.* (2010). The results will be compared with the classical models described by (Stewart, 1976) and (Glauert, 1935).

2. WIND CONDITIONS OF SÃO TOMÉ

In September 2003, through a project financed by the bottom CT-Petro, a system was implemented hybrid photovoltaic-wind-diesel in the village of São Tomé, 67 consumer units aimed at meeting the village. Through this project it was possible to map the velocity profile over 1 year. The collection was developed to a height of 30 m with obtaining data every 10 minutes. Figure 1 shows the density of speed to the village of São Tomé.

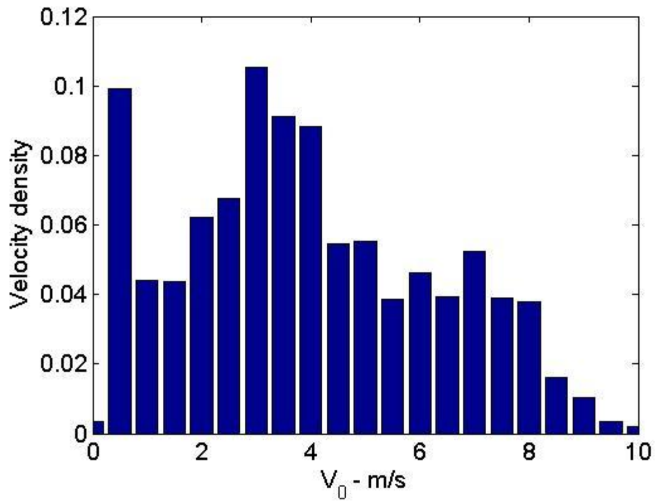


Figure 1. Velocity density for locality of São Tomé.

The fig. 2 shows the energy density available in São Tomé, where the wind speed associated with a higher occurrence of energy is in the range 6-9 m/s. Therefore, São Tomé has the characteristic of a locality with low wind speeds, indicating that the recovery needs to be associated with wind turbine design should be conditioned to this wind regime.

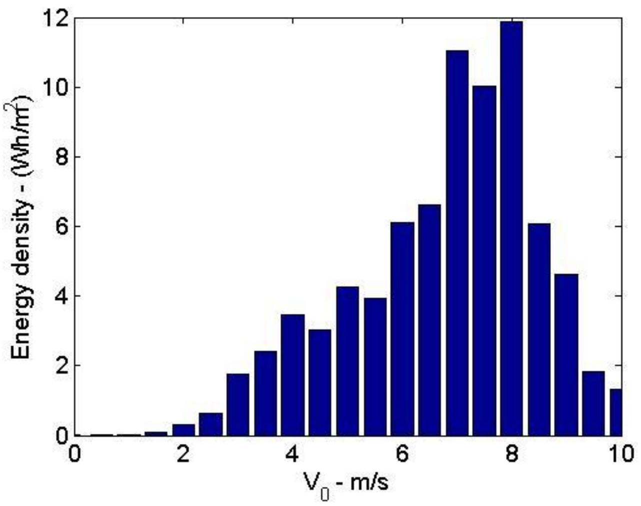


Figure 2. Energy density for locality of São Tomé.

3. CHARACTERISTICS OF SELIG 1223 AERODYNAMIC PROFILE

The Selig 1223 airfoil was designed by Michael Selig for the SAE R/C small airplane competition for weight lifting. This heavy-lift airfoil was designed to provide 30% more lift than the FX 63-137 airfoil, which to date has been one of the favorites for the competition Silva et al. (2002). In this work will be developed the design of a wind turbine using the Selig 1223 aerodynamic profile and compared with a turbine available in the market. Figure 3 show the Selig 1223 aerodynamic profile.

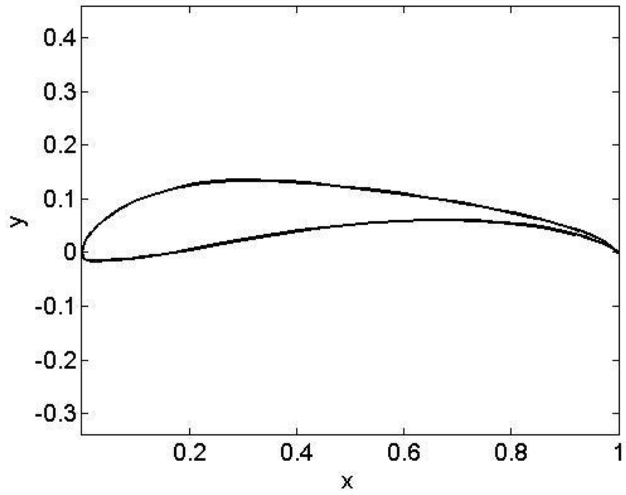


Figure 3. Selig 1223 airfoil geometry.

The Figures 4 and 5 shows experimental data for the lift and drag coefficients for a Reynolds number 2.991×10^5. The data were obtained of wind tunnel analyses Selig et al. (1996a).

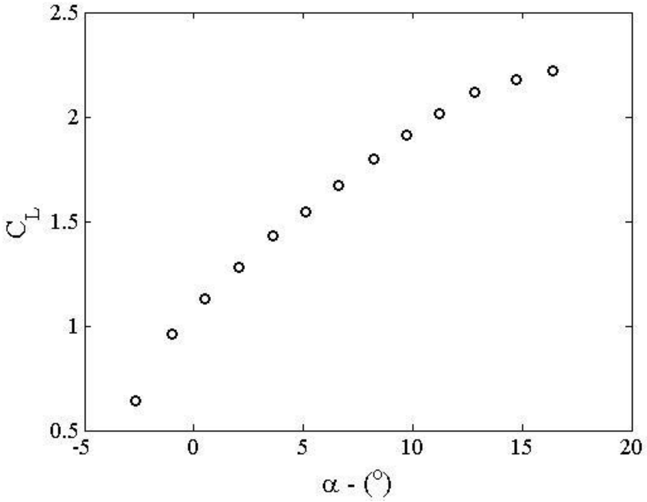


Figure 4. Lift coefficient vs. angle of attack.

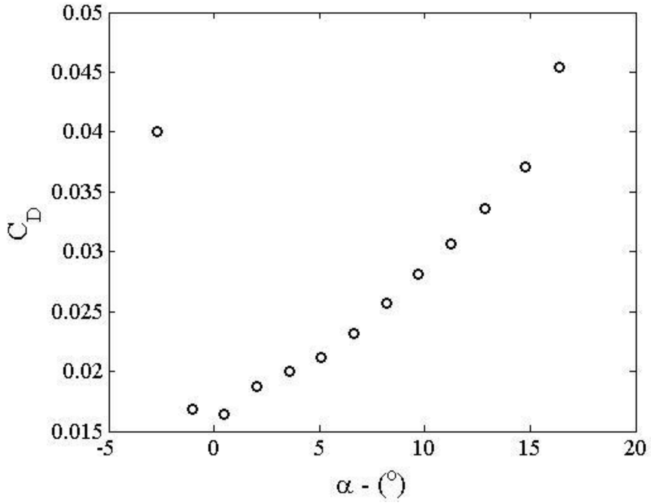


Figure 5. Drag coefficient vs. angle of attack.

4. MATHEMATICAL MODEL FOR WIND ROTOR DESIGN

A flow model that considers the complete equations of angular momentum for the wake rotational, was presented by (Joukowski, 1918), applied by (Glauert,1926a) in the study of propellants, and later modified by (Wilson and Lissaman, 1974) for the case of the wind rotor design, where the induction caused by the wake flow is twice the induction in the rotor plane. Figure 6 shows a scheme for the behavior of the flow in a currents tube (Hansen, 2000).

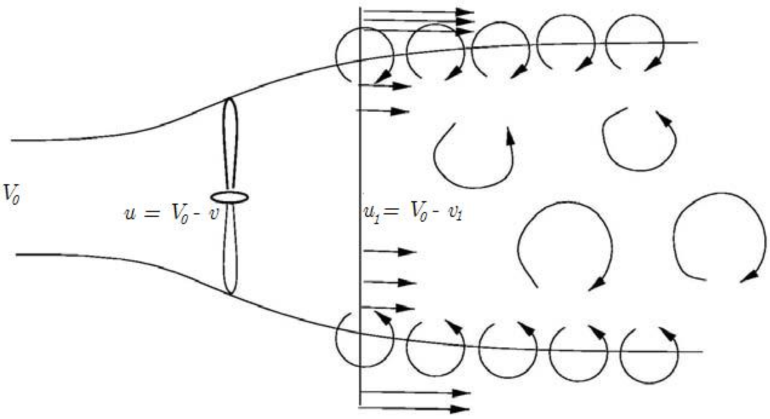


Figure 6. Simplified scheme of velocity on a wind turbine (adapted of Hansen, 2000).

u and u_1 are the induced velocities on the rotor plane and the wake, respectively, are:

$$\begin{cases} V_0 - v = u \equiv \ 1-a \ V_0 \\ V_0 - v_1 = u_1 \equiv \ 1-b \ V_0 \end{cases} \tag{1}$$

where $v = aV_0$ and $v_1 = bV_0$ is the velocity of undisturbed flow, a and b are the axial induction factors on the rotor plane and the wake, respectively. Applying the energy equation (detailed in the works of Eggleston and Stoddard, 1987) and (Wilson and Lissama, 1974) for the induced velocities, Eq. (1), determinate a general relation between inductions factors on the rotor plane and the wake, Eq. (2).

$$a = \frac{b}{2}\left[1 - \frac{b^2 \ 1-a}{4X^2 \ b-a}\right] \tag{2}$$

where X is the tip-speed-ratio. Eq. (2) present a non-linear relation between a and b for low tip-speed-ratio, principally $X < 2$, show in fig. 7.

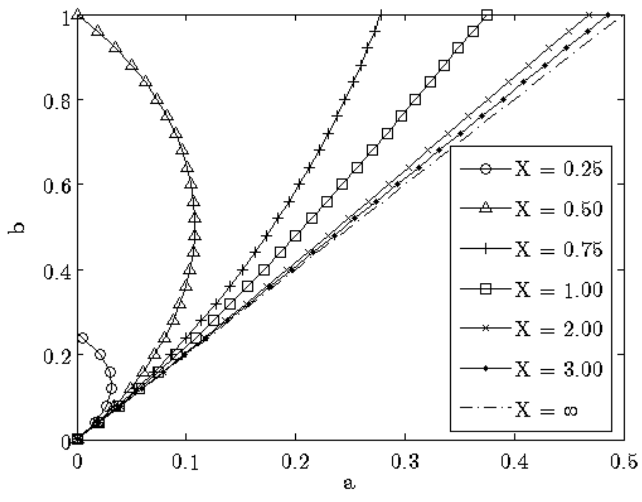


Figure 7. Relation b/a for any values of X (Wilson and Lissaman, 1974).

The coefficient of power in this case has the form of Eq. (3) (Wilson and Lissaman, 1974).

$$Cp = \frac{b^2 (1-a)^2}{b-a} \tag{3}$$

Differentiating the *Cp* with respect to axial induction factor in the rotor plane, to maximize the power coefficient has the value of *a* optimum in Eq. (4).

$$a_{opt} = \frac{b\left(-1+\frac{db}{da}\right)+2\frac{db}{da}-\sqrt{4\left(\frac{db}{da}\right)^2-4b\frac{db}{da}\left(3+\frac{db}{da}\right)+b^2\left[1+14\frac{db}{da}+\left(\frac{db}{da}\right)^2\right]}}{4\frac{db}{da}} \tag{4}$$

For which the correlation is $\frac{db}{da}$ obtained by differentiating Eq. (2).

$$\frac{db}{da} = \frac{8X^2 (a-b)^2 - b^3 (b-1)}{4X^2 (a-b)^2 - ab^2 (a-1)} \tag{5}$$

Equation 4 reduces to the optimal value of *a* predict in the actuator disk theory, where $b = 2a$ and, consequently $\frac{db}{da} = 2$, for *X* > 2, resulting in $a_{opt} = \frac{1}{3}$ (Eggleston e Stoddard, 1987). The Figure 8 shows the profiles of induction factors along the blade in this work. Note that the behavior of the parameters *b* and *b'* are different from those used by (Glauert, 1926a), where $b = 2a$ e $b' = 2a'$, considering the induction factors in the wake of the double induction factors in terms of ruptured at any range of operation of the machine. This aspect does not consider the nonlinearity introduced by Eq. (2) in the regime of low tip-speed-ratio, as seen in fig. 8.

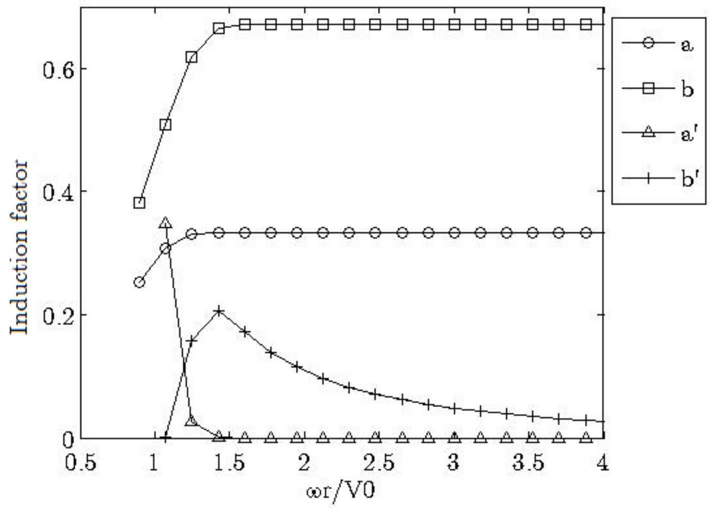


Figure 8. Behavior of axial induction factor on the rotor plane and the wake.

The Figure 9 shows that the proposed optimization results in a tendency for power coefficient to ensure maximum efficiency of the rotor according to the Betz limit (Betz, 1919).

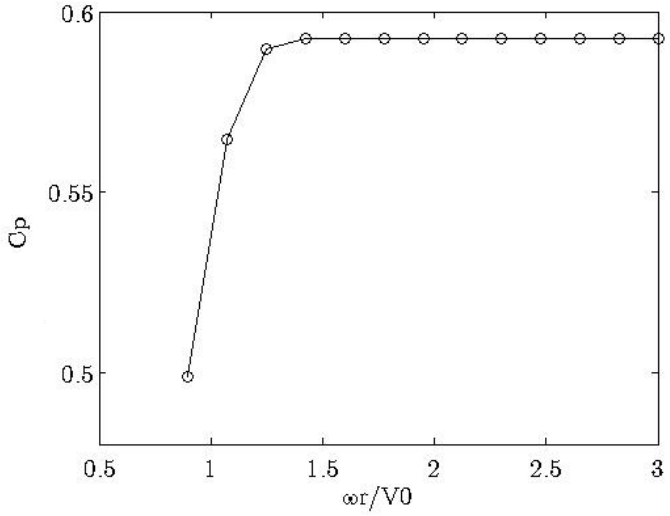


Figure 9. Behavior of local power coefficient.

Therefore, with the value of a_{opt} calculated in Eq. (4) it is possible to calculate the optimal value of the chord through Eq. (6).

$$c_{opt} = \frac{4\pi r b F \sin^2 \ \phi}{B C_n \ \ 1 - a_{opt}} \tag{6}$$

where

$$C_n = C_l \cos\phi + C_d \sin\phi \tag{7}$$

C_l and C_d are the lift and drag coefficients, respectively, which are usually obtained from wind tunnel tests. Equation (6) and Eq. (9) can be verified in detail in the work of (Mesquita and Alves, 2000). Vaz *et al.* (2010) used for the calculation of *a'* the hypothesis that the optimum ratio based on the disk actuator theory, Eq. (8), is valid to optimization of *a'*. However, this assumption is not valid for values of *X* smaller than 2, since the condition $b = 2a$ rescues established in the second disk actuator theory for any value of *X*.

$$a'_{opt} = \frac{1 - 3a_{opt}}{4a_{opt} - 1} \tag{8}$$

In the present work will be considered the relationship given by Eq. (9), which can be obtained from the equation for the angle of flow in the rotor plane.

$$a'_{opt} = \left[\frac{1 - a_{opt}}{x \tan\phi}\right] - 1 \tag{9}$$

The use of Eq. (9), unlike the hypothesis established by Vaz *et al*. (2010) is valid even for values of tip-speed-ratio less than 2, showing that the method proposed in this paper improves the model of Vaz *et al.* (2010). Once calculated a'_{opt} , it is estimated *b'*.

$$b'_{opt} = \frac{1 + a'_{opt} \ \ \sigma C_t}{2F \sin\phi \cos\phi} \tag{10}$$

where

$$\sigma = \frac{cB}{2\pi r} \tag{11}$$

and

$$C_t = C_l \sin\phi - C_d \cos\phi \qquad (12)$$

The optimum angle of flow ϕ is calculated making:

$$\phi_{opt} = \tan^{-1}\left[\frac{1-a_{opt}}{1+a'_{opt}\;x}\right] \qquad (13)$$

where the local velocity ratio is:

$$x = \frac{\omega r}{V_0} \qquad (14)$$

Finally the optimum twist angle is given by:

$$\beta_{opt} = \phi_{opt} - \alpha \qquad (15)$$

5. RESULTS AND DISCUSSIONS

Figures 10 and 11 shows the results obtained using the proposed model and compared with the (Stewart, 1976) model. Note that near the blade root the chord and twist angle are higher in the case of proposed model indicating that for low tip-speed-ratio the blades wide are most appropriate, since the model based on the disk actuator failure in this operation regime of the turbine.

The wind speed used in the design is 7.5 m/s. The choice of this wind speed was based in the energy density, show in the fig. 2, where the higher energy for the locality of São Tomé is around of 7.5 m/s. For the wind turbine design is essential to know the velocity profile of region.

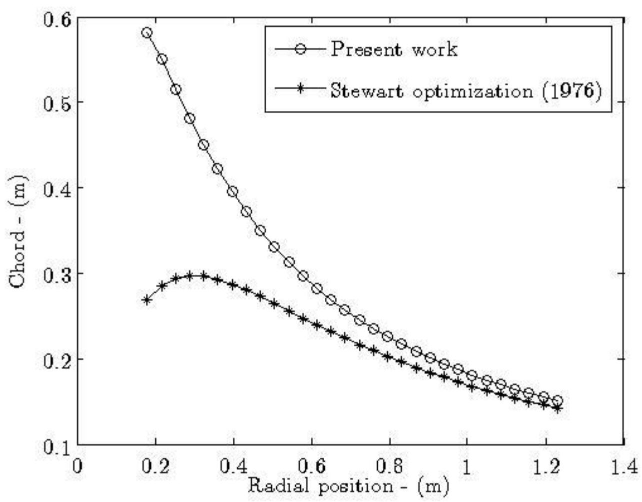


Figure 10. Chord distribution.

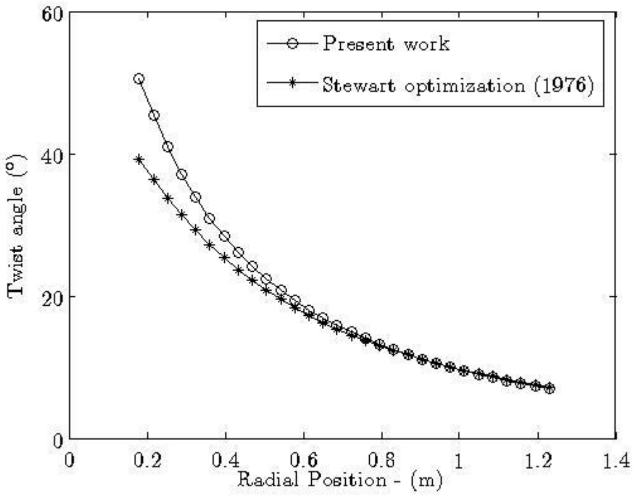


Figure 11. Twist angle distribution.

The trend increase in the chord and the twist angle is predicted by the proposed model, since the root near the tip-speed-ratio is small. Stewart's model does not provide for this operation regime. The Figures 12 and 13 presents the blades designed with chord and twist angle distributions shows in the figs. 10 and 11.

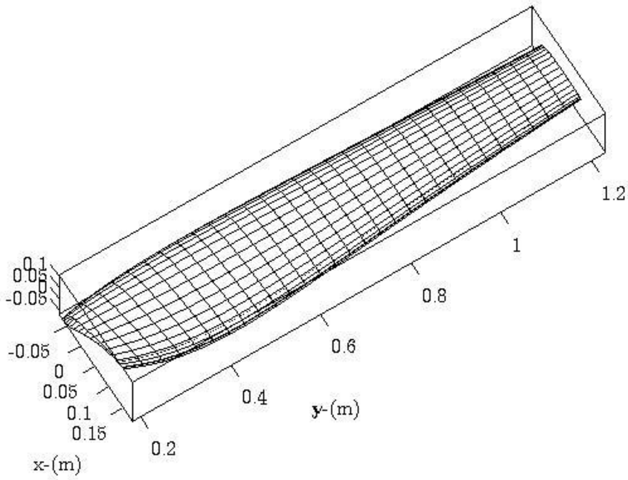


Figure 12. Blade designed using the (Stewart, 1976) model.

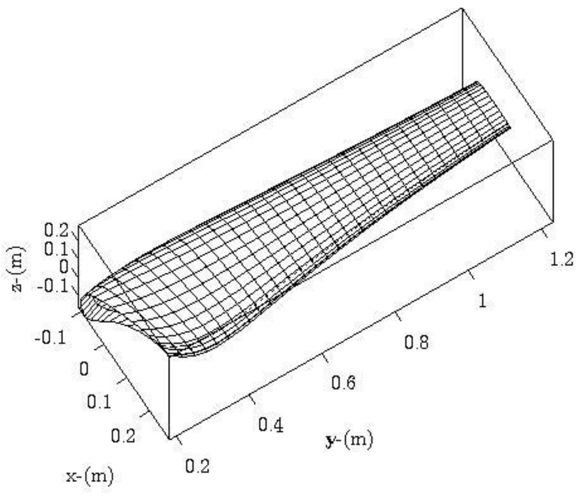


Figure 13. Blade designed using the proposed model.

The power coefficient of turbine designed using the proposed model is compared with experimental data from two turbines available in the market, as a matter of ethics, this work will be marked as turbines A and B, and the results obtained with a turbine designed using the optimization (Stewart, 1976). The data used in the simulation, considering the proposed model and (Stewart, 1976) optimization, and are in Tab. 1:

Table 1. The characteristics of the simulation.

Parameters	Proposed Model
Rotor diameter	2.46 m
Hub diameter	0.36 m
Air density	1226 kg/m3
Turbine rotation	180 rpm
Airfoil	Selig 1223
Number of blades	3
Efficiency of electric generator	80%

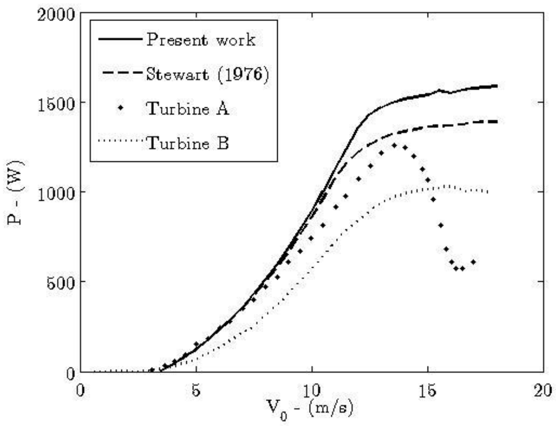
Table 2. The characteristics of the Turbines A and B.

Parameters	Turbine A	Turbine B
Rotor diameter	2.46 m	2.5 m
Number of blades	3	3
Rated power	1000W	1000W
Rated speed	12 m/s	11 m/s
Speed at 12m/s	650 rpm	-

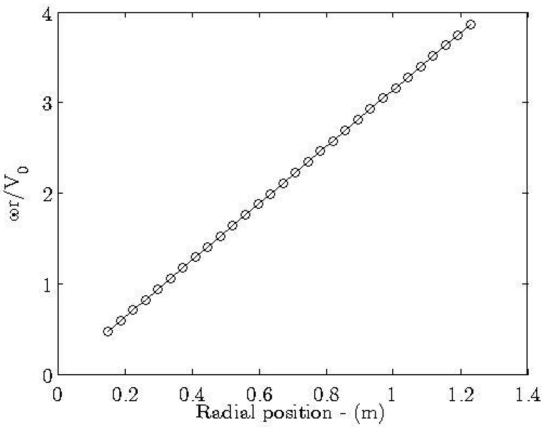
The manufacturer of turbine B has not provided the diameter of the hub, the air density for which testing was performed for the airfoil used, the efficiency of the electrical generator and the rotation speed of 11 m/s.

The results presented in Fig. 14a show that the turbines designed, using the airfoil Selig 1223 (proposed model (Stewart, 1976) optimization) have higher power output compared turbines A and B. This is due to feature high lift Selig 1223 that has hitherto been used only for model airplane (Selig and Guglielmo, 1997b). The Selig 1223 airfoil has a high lift for low Reynolds numbers, which makes it suitable for design of wind turbines small energy demands facing small isolated communities, such as the Village of São Tomé. In calculating the power coefficient of the turbine was developed, considering the speed constant at 180 rpm. Note that the turbine A reaches the rated power of 1000 W with a rotation of 650 rpm for a wind velocity of 12 m/s, while the turbine designed in this paper achieves the same power with speed 10 m/s for a rotating far less, in this case 180 rpm.

The Figure 14a also shows that the turbine designed with the proposed model has higher output power turbine designed by the classical model of (Stewart, 1976). This aspect issue to greater chord and torsion angle obtained with the proposed model, due to tip-speed-ratio is less than 2 near the turbine shaft, as shown in fig. 14b, where the influence of the axial induction factor in the wake is non-linear on the efficiency of the rotor (Wilson and Lissaman, 1974), seen in fig. 7.



(a)



(b)

Figure 14. (a) Comparison between the power developed by the turbines; (b) tip-speed-ratio vs. radial position.

Table 3 present the electrical energy generate by each turbines, where the design of wind turbine through the proposed model has higher energy production for wind velocity profile of São Tomé than turbine designed using the (Stewart, 1976) model and the turbines A and B.

Table 3. Annual productions of electrical energy by turbines.

Turbines	Annual Production (MWh)
Present work	4.4887
Stewart (1976)	4.3174
Turbine A	2.7722
Turbine B	0.5460

6. CONCLUSIONS

The mathematical model shown is an alternative tool for the optimal design of wind rotors, where the main advantage is that, in its mathematical structure is taking to account the general equation that relates the induction factors in the rotor plane and in the wake, Eq. (2), established by (Wilson and Lissama, 1974). The presented method converges to the classical theory of optimization of (Stewart, 1976), satisfying the condition set by (Betz, 1919), where the maximum energy to be extracted from the flow is 59.26%. The performance the induction factors in the wake is completely free for non-linear low speed reasons, indicating the need for formulations that meet these characteristics, once again, that this fact represents the regime in which the rotor operates more slowly. The turbine projected using the proposed model shows better performance as compared with the models of the turbines of (Stewart, 1976) and the turbines A and B from São Tomé, meaning that the model can be applied especially to the design of wind rotors that operate with tip-speed-ratio less than 2.

7. ACKNOWLEDGMENTS

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