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ANNUAL ENERGY PRODUCTION FROM A HORIZONTAL AXIS SMALL WIND TURBINE USING NACA 4412 AIRFOIL

Willian Minoru Okita, minoruokita@gmail.com
Luis Felipe Mendes de Moura, felipe@fem.unicamp.br
Kamal Abdel Radi Ismail, kamal@fem.unicamp.br

University of Campinas, Department of Mechanical Engineering, Campinas, Brazil

Abstract. *Climatic changes and global warming resulting from the human activities and energy utilization, alerted the world about the irreversible consequences and the urgency to interfere in the current environment scenario, intensify research for other sustainable energy alternatives and establish limits for energy production and consumption. Among the most viable energy sources wind energy stands at the top of the list with dominated technology well accepted by population. In this paper, we propose a method for finding maximum annual energy production (AEP) by designing the wind turbine blade geometry for different wind speeds in Campinas region. An algorithm based on the Blade Element Momentum (BEM) method and Weibull distribution was developed on Matlab. The results show that the blade design with rated wind speed of 7 m/s, produced annual energy of about 20.453 MWh/year, with a probability of occurrence of wind speed of 4.3%. Therefore, determining the best geometry to increase the AEP, will contribute to energy production and will decrease the dependency on non-renewable energy sources.*

Keywords: *wind turbine, Blade Element Momentum theory, annual energy production, blade geometry.*

1. INTRODUCTION

Energy is one of the crucial inputs for socio-economic development of a country. The rate at which energy is being consumed by a nation often reflects the level of prosperity that it could achieve. Social and economic welfare is usually measured by the energy consumption, which can reach 9000 kilograms of oil equitant per annum per person in comparison with most developing nations where the energy consumption is usually below 500 *kg* oil equivalent. The increase of global population is another aspect, which is linked to energy consumption.

The global energy demand is usually met by a variety of sources. Fossil fuels consisting of coal, oil, and natural gas meet around 80 percent of the needs with a small contribution from renewable sources (wind, solar etc.) of about 2.2%. Fossil fuels are finite and will be completely exhausted in the near future leading to possible global energy crisis (UNDP, 2004).

Environmental effects of fossil fuel due to power generation and energy consumption add another dimension to the problem. The power production and energy utilization load the atmosphere with greenhouse gases (GHG) and particulates, responsible for 50 to 60 per cent of GHG released into the atmosphere on a global basis. With the increase in energy use, atmospheric pollution from the energy sector is expected to increase further in the near future. Several efforts are being realized globally to reduce the level of atmospheric pollution due to the human activities. Sustainable energy sources like solar and wind are among the viable solutions (Sathyajith, 2006)

Due to the global commitment to reduce the GHG emissions and provide sustainable energy sources to the developing world, efforts are being made to supplement the world energy base with renewable sources. Several countries have already formulated policies frameworks to ensure that renewable sources play an impressive role in the future energy scenario. Wind, is one of the commercially viable and economically competitive renewable sources. The total global installed capacity is 39434 *MW* in 2004. Over 73% of the global installations are in Europe. Germany is the European leader, followed by Spain and Denmark (Islam, 2007, Solanki, 2008).

Therefore, the wind turbines have become an option to produce sustainable energy. So, methods were developed to improve performance in order to depend less on non-renewable energy sources.

The objective of this work is to propose a method for determining maximum annual energy production (AEP) by designing the wind turbine blade geometry for different wind speed in Campinas region.

2. FORMULATION AND COMPUTATIONAL PROCEDURE

2.1 Mathematical formulation

In this work, the algorithm was based on the Blade Element Momentum (BEM) method. The thrust from the disc on the control volume shown in Figure 1, can be found from the integral momentum equation since the cross-section area of the control volume at the rotor plane is $2\pi r dr$. The torque dM on the annular element is found using the integral moment of momentum equation on the control volume (Hansen, 2008).
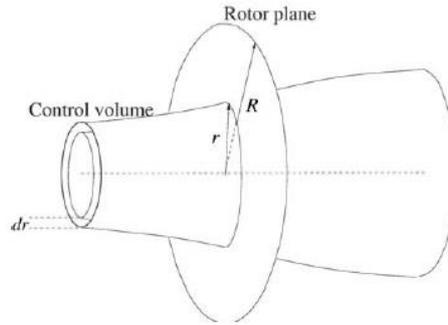

Figure 1: Control volume shaped as an annular element to be used in the BEM model (Hansen, 2008).

$$dT = \rho V^2 4a(1 - a)\pi r dr \tag{1}$$

$$dM = 4a'(1 - a)\rho V\pi r^3 \omega dr \tag{2}$$

Where ρ is the air density, V is the mean air flow velocity, r is the local blade radius, ω is the blade angular rotational speed, a and a' are the axial and the tangential induction factors, respectively.

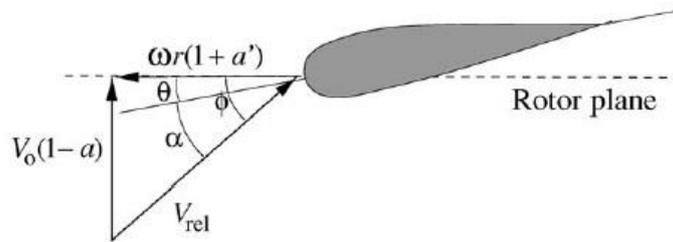According to the blade element theory and by referring to Figure 2, one also has:

Figure 2: Velocities at the rotor plane (Hansen, 2008).

$$dT = \frac{1}{2}\rho B \frac{V^2 (1 - a)^2}{sin^2 \phi} cC_n dr \tag{3}$$

$$dM = \frac{1}{2}\rho B \frac{V(1 - a)\omega r(1 - a')}{sin\phi cos\phi} cC_t r dr \tag{4}$$

Where B is the number of blades and c is the local blade chord length ϕ is the angle of relative wind, dr is the radial length of element, C_n and C_t are the normal and tangential coefficients, respectively.

The summation of dM for all the blades elements gives the total torque (M). Therefore, the wind turbine power is given by $P = M \omega$. Eventually, the wind turbine power prediction lies in solving the axial induction factor a and the tangential induction factor a'. So, through the combination of Equations 1, 2, 3, and 4, one can solve the induction factors a and a' as showed below:

$$a = \frac{1}{\frac{4 sin^2 \phi}{\sigma C_n} + 1}$$

(5)

$$a' = \frac{1}{\frac{4 sin\phi cos\phi}{\sigma C_t} - 1}$$

(6)

2.2 Prandtl's Tip Loss Factor

Prandtl's tip loss factor corrects the assumption of an infinite number of blades. For a rotor with a finite number of blades, the vortex system in the wake is different from that of a rotor with an infinite number of blades. Prandtl derived a correction factor F to equations (1) and (2):

$$dT = \rho V^2 4a(1 - a) F \pi r dr$$

(7)

$$dM = 4a'(1 - a) F \rho V \pi r^3 \omega dr$$

(8)

The F is computed as $F = (2/\pi) cos^{-1}(e^f)$, where $f = (B/2)(R-r/2rsin\phi)$, R is the total radius of the rotor and ϕ is the flow angle. Using equations (7) and (8) instead of equations (1) and (2) in deriving the equations for a and a' yields.

$$a = \frac{1}{\frac{4 F sin^2 \phi}{\sigma C_n} + 1}$$

(9)

$$a' = \frac{1}{\frac{4 F sin\phi cos\phi}{\sigma C_t} - 1}$$

(10)

2.3 Glauert Correction for High Values of a

The expression below is from Spera (1994) where a_c is approximately 0.2 (Glauert, 1935). F is Prandtl's tip loss factor and corrects the assumption of an infinite number of blades.

$$\begin{cases} C_T = 4a(1 - a)F & se \quad a \le a_c \\ C_T = 4(a_c^2 + (1 - 2a_c)a)F & se \quad a \le a_c \end{cases}$$

(11)

From the local aerodynamics the thrust, dT on an annular element is given by equation (3). For an annular control volume, C_T is by definition:

$$C_T = \frac{dT}{\frac{1}{2} U^2 2\pi r dr}$$

(12)

If equation (3) is used for dT, C_T becomes:

$$C_T = \frac{(1 - a)^2 \sigma C_n}{sin^2 \phi}$$

(13)

If $a \le a_c$

$$4a(1 - a)F = \frac{(1 - a)^2 \sigma C_n}{sin^2 \phi}$$

(14)

and this gives:

$$a = \cfrac{1}{\cfrac{4F\sin^2\phi}{\sigma C_n} + 1} \tag{15}$$

If $a > a_c$:

$$4(a_c^2 + (1 - 2a_c)a)F = \frac{(1 - a)^2 \sigma C_n}{\sin^2\phi} \tag{16}$$

we have:

$$a = \frac{1}{2}[2 + K(1 - a_c) - \sqrt{(K(1 - 2a_c) + 2)^2 + 4(Ka_c^2 - 1)]} \tag{17}$$

Where:

$$K = \frac{4F\sin^2\phi}{\sigma C_n} \tag{18}$$

2.4 Annual energy production

In order to compute the annual energy production it is necessary to combine this production curve with a probability density function for the wind. From this function the probability, $f (Vi < Vo < Vi+1)$, that the wind speed lies between Vi and $Vi+1$ can be computed. Multiplying this with the total number of hours per year gives the number of hours per year that the wind speed lies in the interval $Vi < Vo < Vi+1$. Multiplying this by the power (in kW) produced by the wind turbine when the wind speed is between Vi and $Vi+1$ gives the contribution of the total production (in kWh) for this interval (Hansen, 2008).

The probability density function of the wind is given by Weibull distribution. However, some corrections for the local siting (for example for landscape, vegetation, and nearby houses and other obstacles) can be modelled through a scaling factor A and a form factor k (Hansen, 2008):

$$h_w(V_0) = \frac{k}{A}\left(\frac{V_0}{A}\right)^{k-1} exp\left(-\left(\frac{V_0}{A}\right)^k\right) \tag{19}$$

From the Weibull distribution, the probability $f (Vi < Vo < Vi+1)$ that the wind speed lies between Vi and $Vi+1$ is calculated as:

$$f(V_i < V_0 < V_{i+1}) = exp\left(-\left(\frac{V_i}{A}\right)^k\right) - exp\left(-\left(\frac{V_{i+1}}{A}\right)^k\right) \tag{20}$$

When the $(\bar{V})$ is the average wind speed, (k) is the form factor and (A) is the scale factor in which can be determined using Equation (21):

$$\frac{A}{\bar{V}} = 4.534(0.568 + 0.433/k)^{-1/k} \tag{21}$$

The total annual energy production can thus be evaluated as:

$$AEP = \sum_{i=1}^{N-1} \frac{1}{2}(P(V_{i+1}) + P(V_i))f(V_i < V_0 < V_{i+1}) \cdot 8760 \tag{22}$$

2.5 Calculation Procedure

The BEM method and Weibull distribution were elaborated for the software Matlab to evaluate the AEP. The BEM method is chosen because it is the classical and couples the momentum theory with the local events taking place at the blades. It can calculate the steady loads, the thrust and power for different values of wind speed, rotational speed and pitch angle. The Weibull distribution is a statistical treatment of wind speed.

The nominal conditions for a standard wind turbine are presented in the Table 1. The estimated nominal conditions are: power coefficient (C_p), tip speed ratio (λ), angular velocity (ω). Initially, the rotor radius is estimated from equation (1).

Table 1 – Nominal condition for the standard wind turbine

Parameters	Values
Power (P)	10 kW
Speed (V)	10 m/s
Rotation frequency (ROT)	243.5 rpm
Density (ρ)	1.255 kg/ m^3
Efficiency (η)	0.85
Number of blades (B)	3
Airfoil	NACA 4412

$$R = \sqrt{\frac{2P}{\pi \rho \eta C_p V^3}} \qquad (23)$$

While the angular velocity:

$$\omega = 2\pi \frac{ROT}{60} \qquad (24)$$

However, there is an iterative part of the blade length which is used to attach the blades to the hub considered here as 15% R.

The tip speed ratio is calculated from Equation (25):

$$\lambda = \frac{\omega R}{V} \qquad (25)$$

The geometry parameters as twist angle and chord can be calculated by Equations (26) and (27) (Manwell, 2009) respectively:

$$\theta = \phi - \alpha \qquad (26)$$

$$c = 8\pi R \frac{1 - \cos \phi}{BC_1} \qquad (27)$$

Where: α is the attack of angle, C_1 is lift coefficient.
Following (Hansen, 2008) as showed in Figure 3:

Step (1): Initialize the axial induction factor (a) and tangential induction factor (a'), typicall y=a'=a

Step (2): Compute the flow angle ϕ using
$$\tan\phi = \frac{(1 - a)V}{(1 - a')\omega r}$$
where r is the radius

Step (3): Compute the local angle of attack using $\alpha = \phi - \theta$.

Step (4): Estimate off lift coefficient $C_l(\alpha)$ and drag coefficient $C_d(\alpha)$ from table.

Step (5): Compute normal coefficient (C_n) and tangential coefficient (C_t) from equations $C_n = C_l\cos\phi + C_d\sin\phi$ and $C_t = C_l\sin\phi - C_d\cos\phi$

Step (6): Calculate a, if $a < a_c$ use Equation (15), and if $a > a_c$ use Equation (17), calculate a'.

Step (7): If a and a' has changed more than a certain tolerance, go to step (2) or else go to step (8).

Step (8) : Calculate the thrust using the Equation (8).

Step (9): Integrate $dP = \omega dM$ to determine the power along the blade.

Step (10): Calculate the probability of occurrence of wind speed for the region of Campinas using the Equation (20).

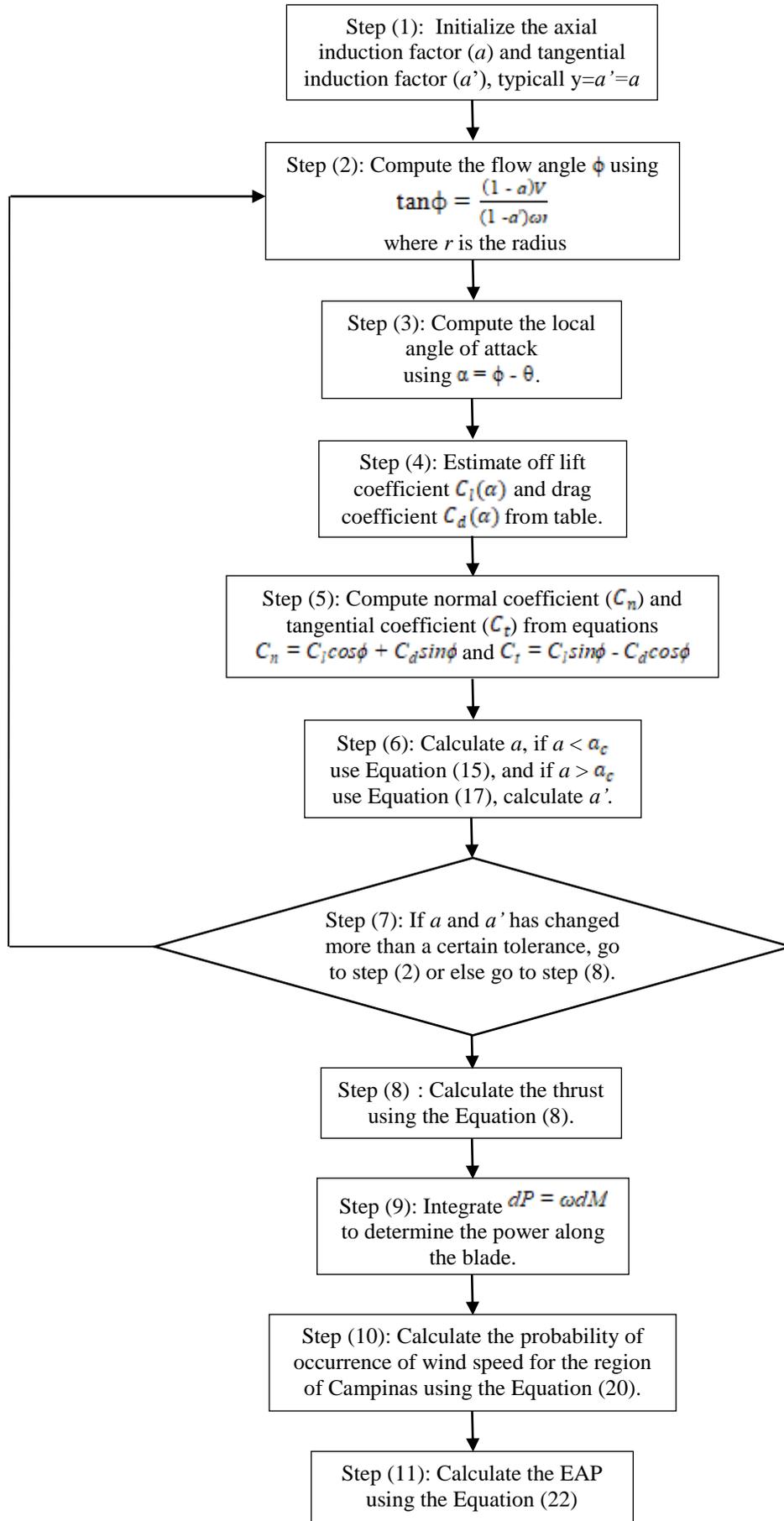Step (11): Calculate the EAP using the Equation (22)

Figure 3: Flowchart of the BEM and Weibull method to calculate the AEP

3. RESULTS AND DISCUSSION

To determinate the probability of occurrence of wind speed we used the wind map of the State of São Paulo 2012. Therefore, for a height of 50 meters the average wind speed is 5 *m/s*, the form factor is 1.8 and scale factor is 5.627 *m/s* (Secretary of Energy, 2012). In this work, we considered the wind turbine as ideal, so the entire speed range used was 0 to 20 *m/s*. By using these values, Figure 4 was prepared.
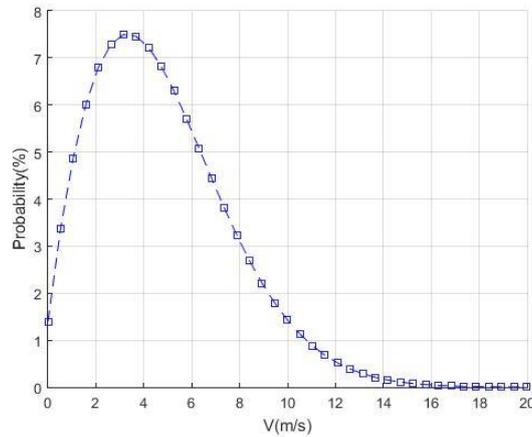

Figure 4: Probability in function of speed

Table 2 shows the AEP for different speed, where the highest energy is 20.453 *MWh*/year, presenting nominal wind speed of 7 m/s, C_p=0.55.

Table 2 – Annual energy production for the Campinas region designed for different speed

Speed (*m/s*)	Tip speed ratio (λ)	Power coefficient (C_p)	Annual energy production (*MWh*/year)
3	24	0.491	8.307
4	17.5	0.521	13.328
5	14	0.539	17.142
6	11.7	0.547	19.734
7	9.6	0.550	20.453
8	8.5	0.551	18.740
9	7.4	0.551	14.682
10	6.3	0.555	8.940

The following the results present the wind turbine project using the nominal velocity estimated of 7m/s.

3.1 Tip blade speed ratio

Despite value of λ has been chosen based in nominal velocity of wind that presented bigger annual energy production, we can observe in Figure 5 that the value of λ also resulted in the bigger value of Cp for this same nominal wind velocity, where λ = 9.6 e Cp = 0.550.
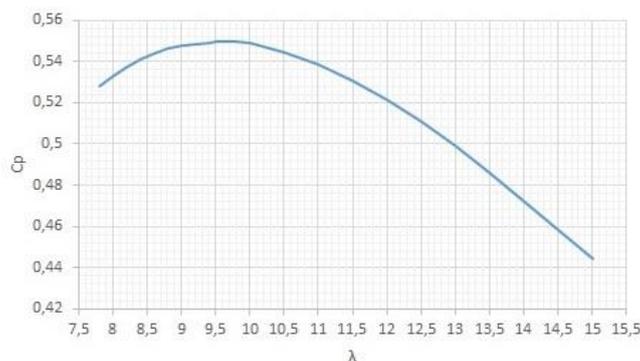

Figura 5: Power coeffcient as a function of the tip speed ratio

3.2 Geometrical parameters

The local characteristic: the ratio Cl/Cd, flow angle, pitch angle, effective angle of attack and chord for the wind turbine designed Campinas region are showed in Table 3.

Table 3: Results for blade element

Blade Element	Radius [m]	Cl/Cd	Flow angle [°]	Pitch angle [°]	Angle of attack [°]	Chord [m]
1	0.523	114.847	21.573	16.323	2.154	0.331
2	0.592	115.437	19.590	14.340	2.219	0.302
3	0.662	116.048	17.901	12.651	2.295	0.277
4	0.731	116.644	16.455	11.205	2.377	0.255
5	0.800	117.242	15.209	9.959	2.460	0.236
6	0.869	117.941	14.127	8.877	2.543	0.220
7	0.938	118.710	13.182	7.932	2.624	0.205
8	1.008	119.453	12.350	7.100	2.703	0.193
9	1.077	120.101	11.613	6.363	2.778	0.181
10	1.146	120.631	10.956	5.706	2.851	0.171
11	1.215	121.132	10.367	5.117	2.921	0.162
12	1.284	121.607	9.837	4.587	2.988	0.154
13	1.354	122.056	9.357	4.107	3.052	0.146
14	1.423	122.482	8.921	3.671	3.113	0.14
15	1.492	122.884	8.523	3.273	3.171	0.133
16	1.561	123.265	8.158	2.908	3.227	0.128
17	1.631	123.550	7.823	2.573	3.277	0.123
18	1.700	123.790	7.514	2.264	3.327	0.118
19	1.769	124.017	7.228	1.978	3.375	0.113
20	1.838	124.232	6.963	1.713	3.421	0.109
21	1.907	124.436	6.716	1.466	3.465	0.105
22	1.977	124.641	6.486	1.236	3.507	0.102
23	2.046	124.886	6.271	1.021	3.547	0.098
24	2.115	125.120	6.070	0.820	3.586	0.095
25	2.184	125.343	5.881	0.631	3.622	0.092
26	2.253	125.556	5.703	0.453	3.658	0.090
27	2.323	125.759	5.536	0.286	3.691	0.087
28	2.392	125.952	5.378	0.128	3.724	0.084
29	2.461	126.135	5.229	-0.021	3.755	0.082
30	2.530	126.308	5.088	-0.162	3.784	0.080
31	2.599	126.528	4.954	-0.296	3.821	0.078
32	2.669	126.676	4.827	-0.423	3.847	0.076
33	2.738	126.805	4.707	-0.543	3.869	0.074
34	2.807	126.902	4.592	-0.658	3.885	0.072
35	2.876	126.950	4.482	-0.768	3.894	0.070
36	2.946	126.912	4.378	-0.872	3.887	0.069
37	3.015	126.717	4.279	-0.971	3.854	0.067
38	3.084	126.216	4.183	-1.067	3.768	0.066
39	3.153	124.956	4.092	-1.158	3.559	0.064
40	3.222	121.259	4.005	-1.245	2.939	0.063

4.7.3 Chord and pitch angle

Figure 6 presents the results of chord and pitch angle as function of the radius. The chord was designed using Cl equal to 1.052 whose value provides better aerodynamic performance. To determinate, the pitch angle were considered an angle of attack equal to 5.25°, reference to maximum ratio Cl/Cd obtained from the airfoil data.
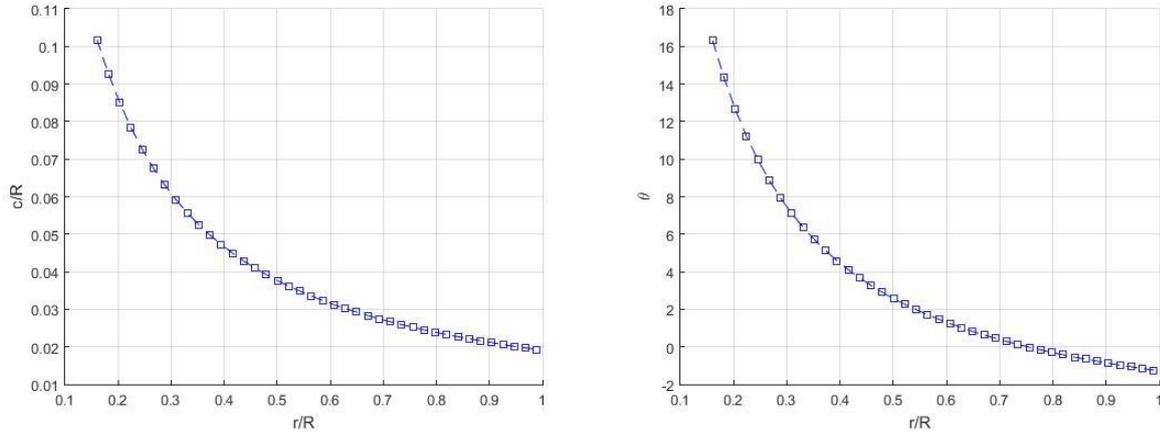

Figura 6: chord and pitch angle as function of the radius

4.7.4 Efficiency and Power

Figures 7 present the power coefficient and power generated, where the maximum power coefficient at the velocity of 7m/s.
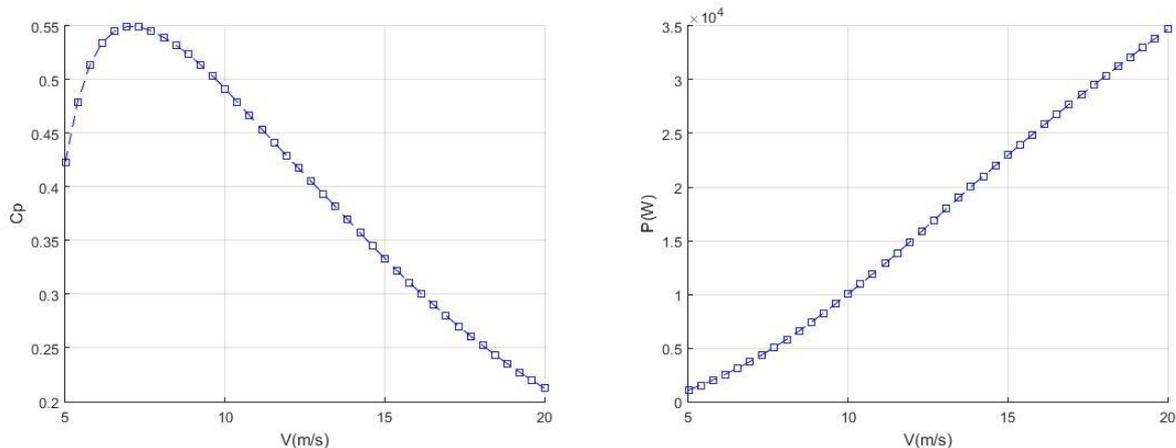

Figura 7: power coefficient and power as function of the wind velocity

4. CONCLUSIONS

From the proposed method it was possible to find the maximum AEP by designing the wind turbine blade geometry for different wind speeds. This can contribute to increase the production of energy and to decrease the dependency on non-renewable energy sources.

5. REFERENCES

Wind Energy Atlas of the State of São Paulo, Secretary of Energy of the State of São Paulo, 2012.
Glauert, H., The elements of aerofoil and airscrew theory. Second ed. 332 University Press Cambridge, Cambridge, 1935.
Manwell J.F., McGowan J.G., Wind Energy Explained Theory, Design and Application, second ed., John Wiley & Sons Ltd, New Jersey, 2009.
Hansen M.O.L. Aerodynamics of Wind Turbines, second ed., Earthscan, London, 2008.
UNDP, World Energy Council (2004) World energy assessment: overview 2004 update. Bureau for development policy, New York: 25-31

Islam S.A.K.M, Appropriate Renewable Energy Technology Options for Bangladesh, 2007.
Solanki, C. S. ''Renewable Energy Fundamentals- A Practical Guide for Beginners'', 2008.
Sathyajith M. Wind energy: fundamentals, resource analysis and economics. Berlin: Springer, 2006.

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