WIND TURBINE COUPLING LOAD MODELING

Armando Lúcio Ramos de Medeiros, armandolucio@bol.com.br
Alex Maurício Araújo, ama@ufpe.br
Oyama Douglas Queiroz de Oliveira Filho, oyamadouglas@ymail.com
Universidade Federal de Pernambuco, Departamento de Engenharia Mecânica, Av. Prof. Moraes Rego, 1235 - Cidade Universitária, Recife - PE - CEP: 50670-901 | Fone PABX: (81) 2126.8000

Abstract. *Prior knowledge of energy production from a wind turbine is essential in the planning/design phase, both from qualitative and quantitative aspects. This production depends on three basic elements: wind conditions, rotor type of the turbine and the load type, that is, how to make a coupling between the load and the driving part. In the case of wind, it is known that the type of distribution could be characterized by Weibull functions, as a result the wind regime would be modeled by two parameters: average speed and form factor k of the distribution. The performance of the rotor can be characterized by the Power coefficient curve (C_p) versus tip speed ratio (TSR). The specification of the load, however, is a more complex process given the diversity of configurations that these systems can take since they can be mechanical or electrical in nature. In the case of electric charges, the generator may be connected directly to the grid or indirectly through frequency conversion devices so that the rotation of the rotor can be constant or variable, respectively. In this work, the load is represented by an electrical generator coupled indirectly to the network. The various types of coupling can be modeled representing the load torque by an exponential wind speed function through the load parameter n ranging from 0 (inefficient load) and 2 (optimal load). From this set of parameters, the mechanical power on the rotor shaft to be converted partially into electrical power delivered to the network will be determined. The relationship between electrical power and mechanical power defines the electromechanical efficiency of the system. The remaining mechanical power, around 10% is transformed into heat due to mechanical and electrical losses. Three conditions with respect to the variation of electromechanical efficiency with the wind speed were considered in specifying the losses: decreasing, constant and increasing. The main objective of this paper is to determine how the losses change the performance of the system and whether this influence changes the condition of maximum production of electricity.*

Keywords*: energy production; distribution of winds; overall efficiency, electrical losses; loading matching*

1. INTRODUCTION

The performance of a wind turbine operation can be quantified by the production of energy at a given time, being a function of three basic variables: the wind, the rotor type and the load. The modeling of the system is very important from the qualitative aspect, as it enables the correlation between the variables and their respective performance which can be used for both making a prediction of energy production and determining the configuration for maximum production. In this context, both wind modeling and the rotor type are more straightforward. For the wind, it is sufficient to determine the average wind speed V_m and the type of distribution, while obtaining the curve C_p x λ, power coefficient versus tip speed ratio – TSR (tip speed ratio of the blade) is sufficient for the rotor type. On the other hand, the load modeling depends on several factors, including the configuration of the system. Due to the great diversity of Wind Energy Conversion systems (WECS), this work will focus on wind turbines with varying angular velocity for electricity generation, although the model used can be extended to analyze any type of WECS. For the selected type, the load modeling depends on how the load torque, referred to the rotor shaft, varies with wind speed and also how electromechanical losses affect the electric power generated. Since electrical losses arise from both losses in the generator and in the process of converting AC-DC-AC, it is usual to simplify the analysis of the influence of losses. This paper models the electrical and mechanical losses, together, in three distinct cases. For this, the analysis takes into consideration that the electromechanical efficiency, defined by relationship between the electrical power delivered to the network and the mechanical power on the rotor shaft is constant or increasing or decreasing, with the wind speed. The modeling makes possible the analysis of how the three main parameters (wind, rotor and load) influence the condition of the optimal WECS project.

2. WIND

The modeling is done based on Weibull distributions using the concept of reduced wind velocity $x=V/V_m$. Its advantage is that the distribution can be represented only by the shape factor k. As for the energetic aspect of each distribution, it is necessary to focus on the analysis of the frequency distribution $f(x)$ and the distribution of energy density $D(x)$, represented respectively by Eqs. (1) and (2), as shown in Fig. 1.

$$f(x) = k\,\Gamma^k\left(1+\frac{1}{k}\right)x^{k-1}\exp\left[-\Gamma^k\left(1+\frac{1}{k}\right)x^k\right] \tag{1}$$

$$D(x) = \frac{f(x)x^3}{K_E} \tag{2}$$

$$K_{\mathrm{E}} = \frac{\left\langle V^3\right\rangle}{V_m^3} = \int_0^\infty f(x)x^3dx \tag{3}$$

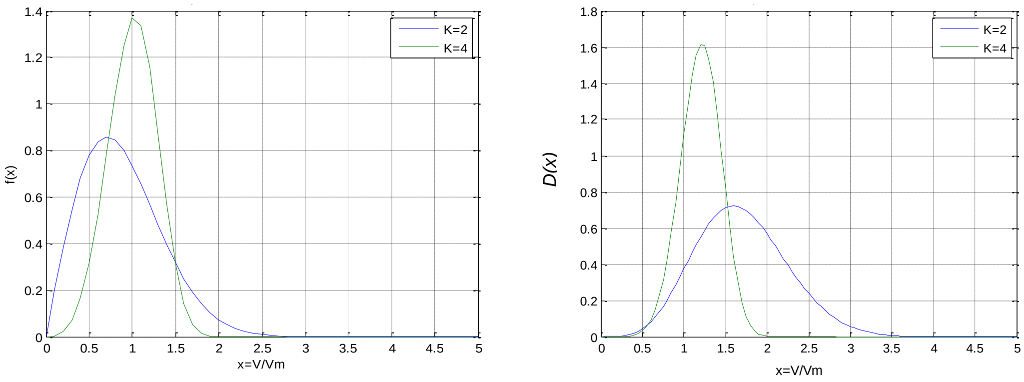


Figure 1. *(a)* Frequency Distribution and *(b)* Energy Density Distribution

where K_E is the energetic factor pattern as defined by the relation between the average of the cubic velocity and the cubic average velocity, according to Eq. (3) (Lysen, 1983). Figure 2 shows how K_E varies with *k*. It should however be emphasized that K_E decreases while *k* increases. In addition, K_E is proportional to the available wind energy in a particular place as it decreases when *k* increases for the same average speed. For example, regarding the northeastern coast where *k = 4*, the energetic content of the distribution is 49,8% relating to that of England where *k = 1.6* for the same average speeds.

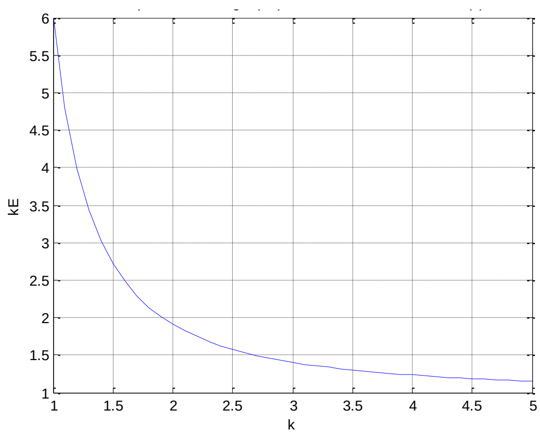


Figure 2. Variation of the energetic factor pattern as a function of *k*

The available wind power at the height of the rotor shaft is given by Eq. (4).

$$P\ (x) = \frac{1}{2}\rho A V_m^3 x^3 \tag{4}$$

where ρ is the air density and *A*, the corresponding swept area by the rotor.

3. ROTOR

The C_p x λ curve, shown in Fig. 3, represents the fraction of the available wind power that is converted by the rotor blades into mechanical power on the axis, for each value of the TSR. This curve can be modified by controlling the pitch of the blades (Burton *et al*., 2008). Figure 3 shows the ranges of $\lambda = \omega r/V$, where ω is the angular velocity of the rotor. The most efficient systems, from the wind energy capturing point of view, operate with C_{pmax} throughout the sub nominal operation range, that is, for power below the rated power P_r. It is useful to note that in the region of nominal operation, the power generated is kept constant by controlling the pitch of the blades (Burton et al, 2008). Figure 4 shows the ranges of operation and the corresponding reduced wind velocity. From the curve C_p x λ, the curve of C_q xλ can be obtained since: C_p=C_q. λ, and hence the mechanical torque calculation on the rotor shaft (T_m) according to Eq. (5).

$$T_m = C_q \, {}^{1}\!/_{2} \rho A R V_m^2 x^2 \tag{5}$$

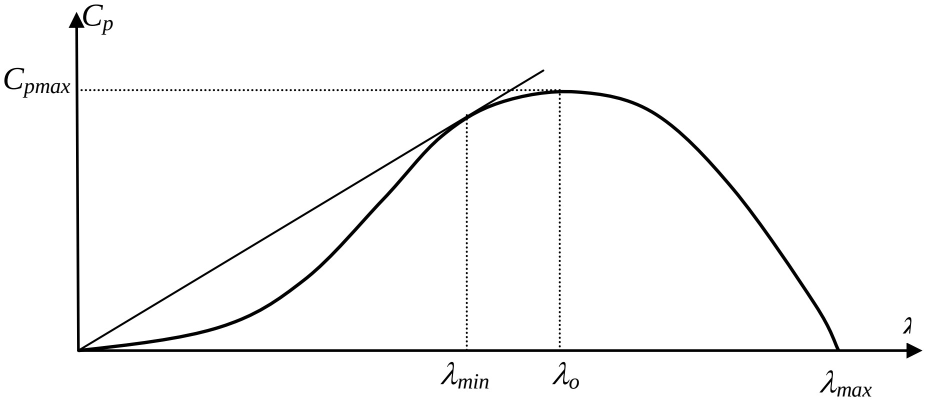


Figure 3. Curve of power coefficient versus TSR

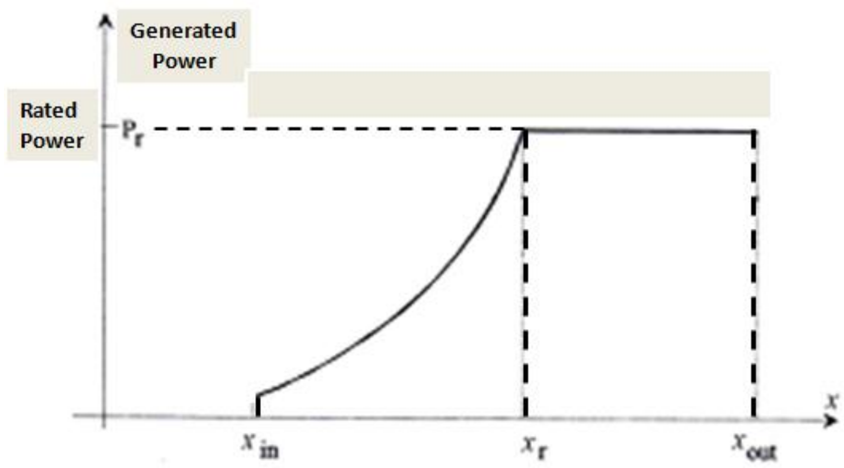


Figure 4. Variation of the generated electrical power versus reduced speed. Medeiros (1995)

When obtained experimentally, the above curve can be used directly to calculate the electrical energy generated (Araújo *et al.*, 2009). The disadvantage is that the curve isn't well defined, since it is influenced by the transient angular velocity of the shaft caused by wind gusts.

4. LOAD

The condition of dynamics equilibrium between the load torque T_c and mechanical torque T_m produced by the blades is shown in Eq. (6).

$$I\omega = T_m - T_c \tag{6}$$

Where I is the moment of inertia of the system referred to the rotor shaft. It is important to see that the steady state (*ss*) condition used here normally, is only real when there are no variations in ω.

Moreover, the mechanical power required by the load P_m must consider two components: the useful power, P_u, related to the electrical power delivered to the network, and the power due to the passive resistance related to electromechanical losses, P_p (Ackermann, 2008). Therefore it can be said that:

$$P_m = P_u + P_p \tag{7}$$

The instantaneous value of the electromechanical efficiency of the system can be written as:

$$\eta_{el-mec} = \frac{P_u}{P_m} = 1 - \frac{P_p}{P_m} \tag{8}$$

It must however be stated the electromechanical efficiency considers only the effects of electromechanical losses. The efficiency represents how much of the mechanical power available at the rotor shaft is converted into electrical power delivered to the network, considering that *ss* conditions are assumed. Thus, the relation below can be established:

$$T_c = K_1 x^n \tag{9}$$

where n represents the load parameter bounded by: $n \le 2$. For optimal load, $n = 2$ which corresponds to the condition with C_{pmax} (C_p constant) is obtained. For smaller values of n, the value of C_p is a variable and therefore the efficiency of the system is lesser. For $n = 0$, a load with constant torque is obtained. This is the case of alternative pumping with multiblade windmills and it represents the least efficient condition.
Figure 5 shows how the value of C_p varies with the reduced speed of the wind, for $k = 2,5$ and n ε {0,5 ; 1,5}. In all the simulations, the curve C_p x λ was used as shown in Fig. 3.

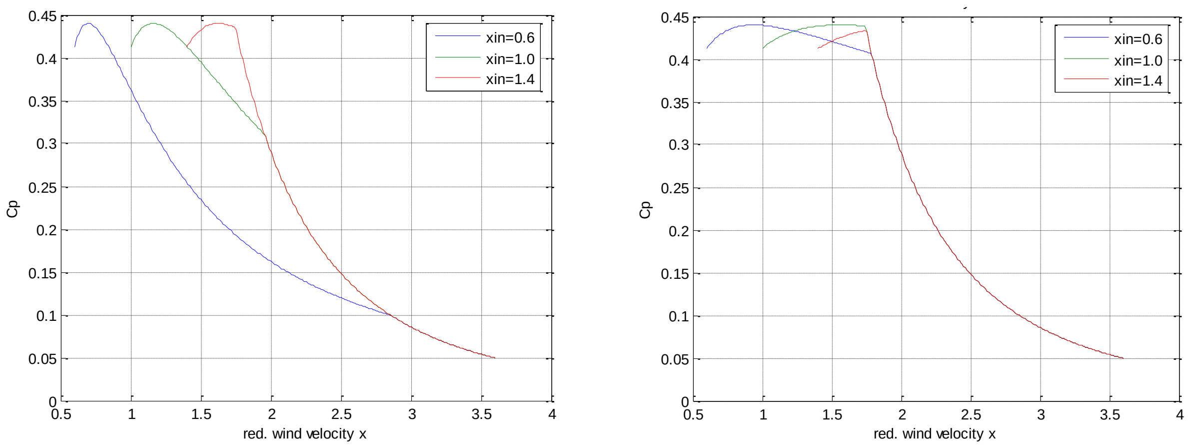


Figure 5. Variation of C_p with the reduced speed x

It should be emphasized that mechanical losses are different from electrical losses. In general, mechanical losses caused by friction in the bearings or in speed multiplier increases with the angular velocity of the shaft, while electrical losses in the process of mechanical-electrical conversion (in the generator) or the frequency conversion process AC-DC-AC, can present a minimum condition in an intermediate angular velocity range for which the generator has been designed. Given the difficulty of precise modeling, in the joint analysis of mechanical and electrical losses, three behavior possibilities were assumed: Losses 1 - Power losses varying linearly with wind speed; Losses 2 - Constant electromechanical efficiency throughout the operation range (equal to 90%) and Losses 3 - Constant power loss (equal to 8% of power rated by WECS). Briefly: the three options imply that the electromechanical efficiency decreases or is constant or increases with the wind speed, respectively as shown in Fig. 6, obtained for k = 2.5 and n = 0.5.

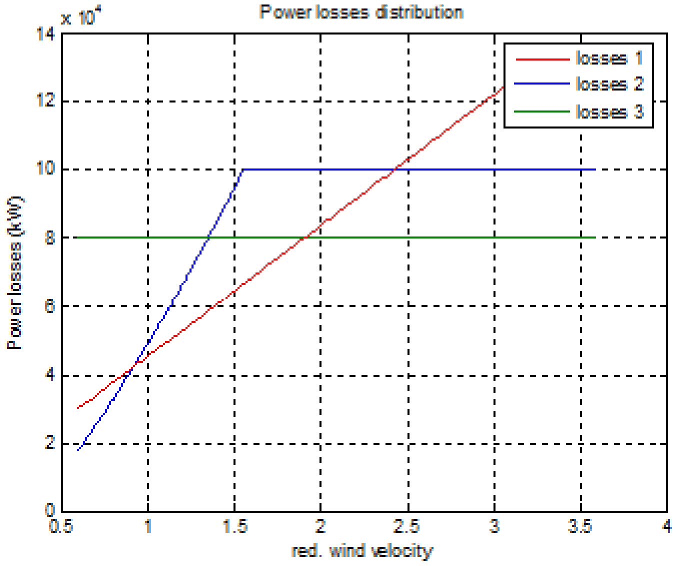


Figure 6. Modeling of electrical losses with respect to the reduced speed *x*

5. PERFORMANCE OF THE SYSTEM

Performance is best measured in terms of electricity production over a given period ΔT. Thus the useful energy produced can be obtained from:

$$E_u = \int_{x_{in}}^{x_{out}} P_u\, dt = \int_{x_{in}}^{x_{out}} \eta_{el-mec}(x) C_p(x) \tfrac{1}{2} \rho A V_m x^3 \, \Delta T \, f(x) dx \tag{10}$$

In addition, the overall efficiency gives directly the fraction of available wind energy that is converted into electrical energy, being a function of the reduced minimum operating speed x_{in}, as defined from the load specification using Eq. (5), considering $C_q = C_{qmax}$.

$$\eta_g = \frac{E_u}{E_{disp}} \tag{11}$$

Figure 7 shows the variation of the overall efficiency for x_{in} ranging from *0.6* to *1.4* for a load with $n = 1.0$ and distribution with $k = 3.0$.

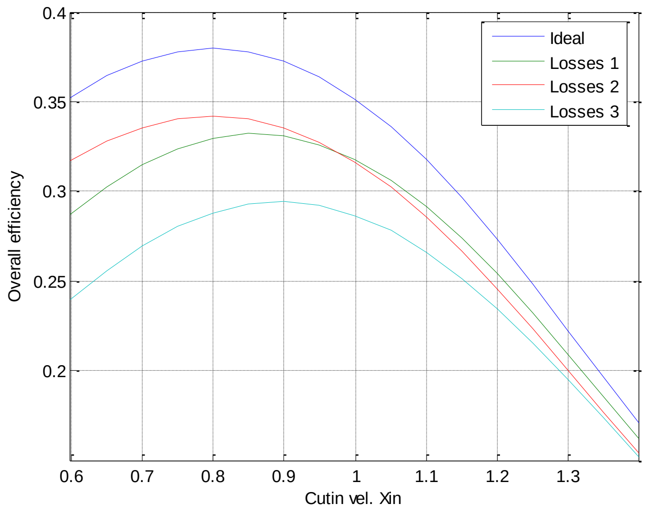


Figure 7. Overall efficiency versus reduced minimum operating speed

6. OPTIMUM PERFORMANCE

Having defined the wind regime of the turbine site, rotor type and type of load, the information necessary to analyze WECS is obtained. However, it is still necessary to define the reduced starting speed x_{st} which by definition, coincides with the reduced minimum operating speed x_{in}. In this situation, the rotor operates with the maximum value of the curve C_q x λ. Actually, the value of x_{in} defines the beginning of the rotor-load coupling which can be used as a performance optimization variable. The smaller the value of x_{in}, the smaller the load torque referred to the rotor shaft. The condition of optimum is related to the maximum production of energy and corresponds to the condition of maximum shown in Fig. 7. General rule: the rotor must operate with the highest C_p values in the range of the highest energy density.

What is the influence on the optimum performance when the electromechanical losses are varied with wind speed? This question is treated in the results shown below.

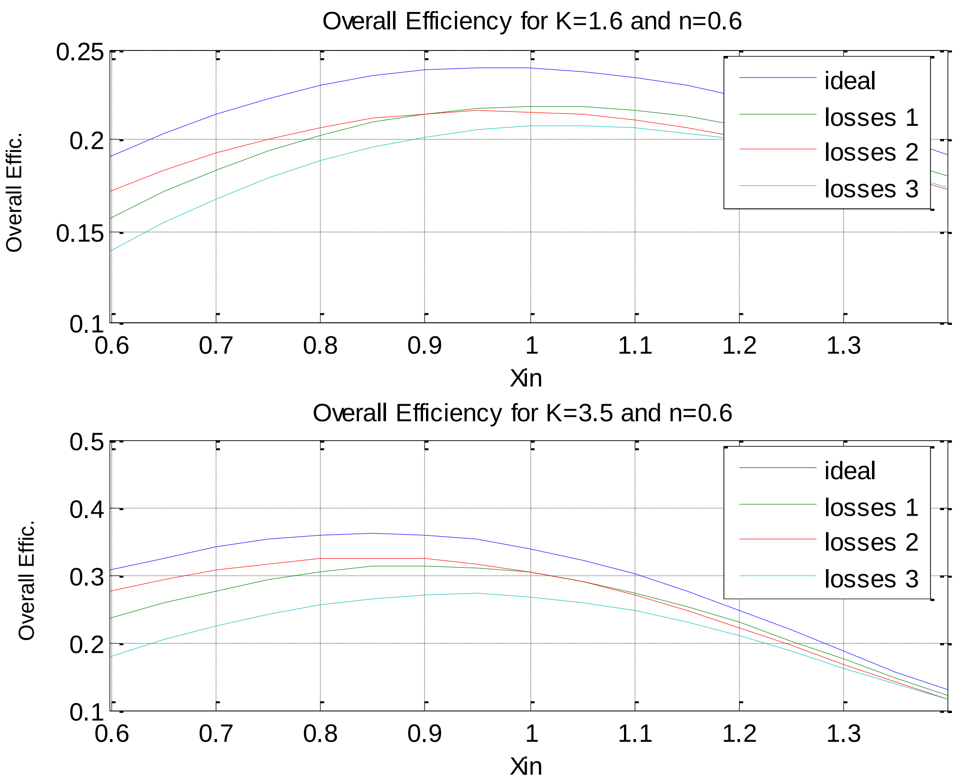
7. SIMULATION

A simulation was performed with a rotor of 60m in diameter, where the TSR of the project is $\lambda = 7$ and $C_{pmax} = 0.44$. As for the wind, $V_m = 6{,}3m/s$ was considered with the following k values: *1.6* and *3.5*. For the load, $n = 0.6$ indicates low performance while $n = 1.6$ indicates high performance.

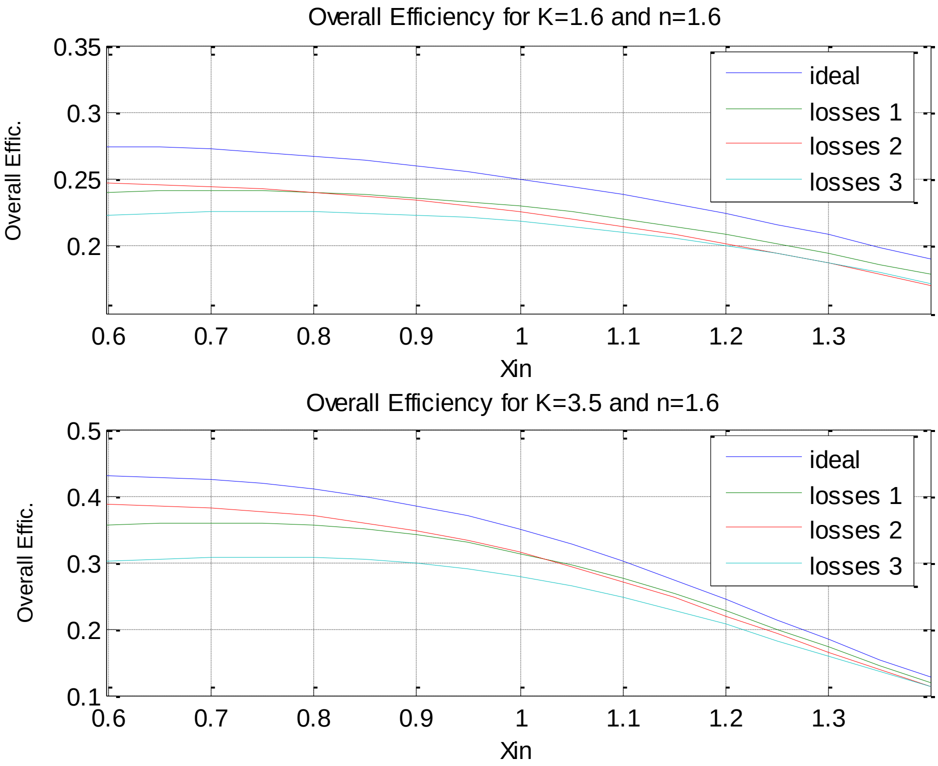
8. RESULTS

The results, shown in the figures below were obtained in terms of the overall efficiency variation by varying x_{in} between *0.6* and *1.4*. The ideal system, with $n = 2$, which operates with $C_p=C_{pmax}=constant$ was taken as a reference for analyzing the other configurations.

Figure 8(b) shows the variation of the overall efficiency for x_{in} ranging from *0.6* to *1.4* for a very efficient load ($n=1.6$) and considering two types of distribution $k=1.6$ and $k=3.5$.



(a)



(b)

Figure 8. Overall efficiency versus speed reduced minimum operating for $k = 1.6$ and 3.5. *(a)* For $n = 0.6$ and *(b)* $n= 1.6$.

9. CONCLUSIONS

From Figs. 8 *(a)* and 8 *(b)*, it is possible to visualize the influence of the type of electromechanical losses on the maximum condition of the overall efficiency. The upper curve, corresponding to an ideal system without losses, presents a well-defined maximum for $n = 0.6$, relative to systems of low performance, with values of $x_{inot} = 0.85$ and $x_{inot} = 1.0$ for $k=3.5$ and $k = 1.6$, respectively, where this behavior is consistent with the energy density curves of Fig. 2. The losses tend to shift slightly the peaks to the left or right depending on their variation type. When the electromechanical efficiency decreases as the reduced wind speed increases (losses 3), the condition of maximum shifts to the left while in losses 1, where the electromechanical efficiency grows, the shift is to the right, both of them varying in the order of 10% of the value of x_{inot}. However, for variations of 10% around the value of x_{inot} variations in the overall efficiency, considering the losses, are very small. In high performance systems, with $n = 1.6$, the maximum of the curves converge to a level on the left and thus becomes insensitive to variations of k and the type of losses. That is, these systems tend to use the full range of possible winds.

From the results discussed above, the specification of the cut-in condition is obtained, in the sense of providing the best load-rotor coupling and therefore the largest energy production, and is significant only for low performance systems, where the parameters k and n are of good relevance. On the other hand, the electromechanical losses reduce the production of energy, but, its shape variation is not significant in the selection of x_{inot}, i.e the condition of the design of the system is not changed.

Regarding the effect of wind distribution on the overall efficiency, the variation of k from 1.6 to 3.5 increases the efficiency to around 50%, for the maximum condition. Considering the effect of K_E that reduces the value of available wind energy by 50%, the production of electricity is reduced by 25%. With respect to the effect of the load type on the efficiency value, the increase in n from 0.6 to 1.6 increases the efficiency to around 15%, considering the conditions of maximum. The influence of the rotor type was analyzed, but its effect is limited to the value of C_{pmax}. The variation of energy production is approximately linear to C_{pmax}.

10. ACKNOWLEDGEMENTS

CAPES: Pro-engineering projects, Project PE-091/2008 and CNPq.

11. RESPONSIBILITY NOTICE

The authors are the only ones responsible for the printed material included in this paper.

12. BIBLIOGRAPHY

Ackermann, T., 2008, "Wind Power in Power Systems", 1st edition, John Wiley & Sons Ltd, England, 691 p.

Araújo, A. M., Melo, G. M., Medeiros, A. L. R., Santos, M. J., 2009, "Simulación de la Producción de Energía Eléctrica con Aerogeneradores de Pequeño Tamaño", Información Tecnológica (Impresa), Vol. 20, pp. 37-44.

Burton, T., Sharpe, D., Jenkis, N., Bossanyi, E., 2008, "Wind Energy Handbook", John Wiley & Sons Ltd, England, 617 p.

Lysen, E.H., 1983, "Introduction to Wind Energy", 2nd edition, SWD Publications, Netherlands, 310 p.

Medeiros, A. L. R., 1995, "Otimização de Sistemas de Conversão de Energia Eólica de Grande Porte", PhD Thesis, Universidade Federal da Paraíba, Campina Grande.

Silva, G. R., 2003, "Características de Vento da Região Nordeste: análise, modelagem e aplicações para projetos de centrais eólicas", Master Thesis, Universidade Federal de Pernambuco, Recife.