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ANALYSIS OF TECHNICAL AND ECONOMIC ASPECTS OF WIND ENERGY CONVERSION SYSTEMS RELATED TO THE CAPACITY FACTOR

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Abstract. *This paper examines how the design parameters of a WECS are related to the capacity factor value and tries to identify which parameters should be used to establish a methodology that ensures the condition of optimized energy production when the system operates under different wind regimes. This is the typical problem of WECS developed by the European community to be installed in Brazil, especially in wind farms located near the northeastern coast. It should be noted that the northeastern wind regime shows little influence of wind gusts resulting in lower energy content, but with reduced loads on the system. The regime type has a great influence on the value of the rated wind speed which is crucial to the value of the Capacity Factor. These parameters are important for WECS reconfiguration and sometimes it is necessary to change the geometry, increasing the tower height or the rotor diameter, fulfilling conditions of lower cost. Reconfiguration of the system indicates that the design parameters must be reassessed so that the system can be adapted to the lowest cost condition in such a way to ensure a power production consistent with the design.*

Keywords: *energy production, distribution of winds, overall efficiency, electrical losses.*

1. INTRODUCTION

This paper aims to analyze the performance of large scale Wind Energy Conversion Systems (WECS) specifically directed to commercial power generation. The performance of WECS, also referred to as wind turbine, could be realized under two distinct aspects: by its global efficiency value η_g and by its Capacity Factor (*CF*). In the first case, η_g reflects the capacity of the system in converting wind energy to electric power. In this aspect, the latest generation of technologies that make use of variable speed rotor, with constant power coefficient, $C_p=C_{pmax}$, are able to maximize the performance of wind/mechanic/electric conversion. Therefore, the use of these technologies, specifically, AC/CC/AC conversion subsystems, was only made viable with the production of large scale wind turbines, which through the scale factor reduced the cost of generated kWh. The value of the *CF* represents the relation between the annual energy yield and the energy that would be generated if the WECS were to be operating under its maximum potential, defined as rated power P_r (Hau, 2006).

In this case, the P_r value is attained always when the wind speed $V \geq V_r$, where V_r is the rated wind speed, predefined by the manufacturer. The calculation of V_r takes two conflicting parameters: cost of the wind turbine and the annual energy production. This way, when the P_r value is increased both the numerator and denominator of the *CF* is also increase, making necessary the establishment of a cost function which minimizes the generated kWh cost. This means that each project has an optimum *CF* value that represents the best relation between the generated annual energy and the cost of the system. On the other hand, the value of V_r defines the rated power of the wind turbine which in turn defined its commercial value. This way, the greater the value of V_r the greater the WECS value. Generally, each wind turbine is optimized to produce power with the lost kWh cost according to a group of pre-established parameters, as a result, when the wind regime is altered, be it due to the type of distribution or by the mean speed value, it becomes necessary to reconfigure the parameters.

Generally, the performance of the system depends on how much electric power can be extracted from wind energy. In this case, the performance depends on its configuration in terms of the local wind regime type, aerodynamics, load type and the load coupling between the rotor and the utilized electric system composed of the generator, AC/CC/AC

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converters, transformer, transmission line, etc. The problem involving the improvement of performance in power production, generally, is due to the presence of a lot of variables that can be grouped under three aspects: 1) technology type: with fixed speed (FS) or variable speed (VS) and with fixed pitch (FP) or variable pitch (VP) ; ii) type of wind regime and iii) reduction of electric losses in the electric conversion system (Hau, 2006; Ackermann, 2005; Burton *et al*., 2001). In this paper, VSVP (Variable Speed Variable Pitch) type of wind turbines which represents the most efficient configuration type will be analyzed (Hau, 2006; Ackermann, 2005; Burton *et al*., 2001). It is important to stress the influence of the WECS operational maintenance cost. Making reference to a wind farm with many units, the *CF* is influenced by the time in which the each wind turbine remains still and, therefore, depends on the type of maintenance: predictive, corrective, etc. This aspect does not alter the global efficiency value that considers that stoppage is related only to low wind speeds.

Boccard (2009) in his paper has shown that the capacity factor of wind power measuring the average energy delivered has been assumed in the 30 - 35% range of the name plate capacity. Yet, the mean realized value for Europe over the last five years is below 21%. He documented this discrepancy and offers rationalizations that emphasize the long term variations of wind speeds, the behavior of the wind power industry, political interference and the mode of finance.

2. WIND REGIME

Generally, the Weibull distributions can represent wind regime, modeled according to the reduced wind speed concept $x=V/V_m$. This becomes an advantage since the wind regime can be represented by the form factor k and by the average speed V_m (Lysen, 1983). Regarding the distribution type, the frequency distribution $f(x)$, given by Eq. (1), is shown in Fig. 1, for $k=1.5$ *e* $k=4$. Besides, the energy density distribution factor $D(x)$, Eq. (2), shown in Fig. 2 how the available wind energy is associated to each wind speed (Medeiros *et al*., 2011). This aspect is relevant in terms of the definition of rated wind speed $V_r = x_r V_m$. From the generation point of view, for $k=4$, typical of the northeast coast (Silva, 2003), reduced wind speed above $x=1.8$ are not observed. On the other hand, about 7% of the registered wind speed, corresponding to 40% of the available wind energy, occurs for $x\geq 1.8$, when $k=2$, typical of North European countries where the major wind turbine manufacturers.

Still on the energetic aspect, the standard energy factor K_E defines the relation between the available wind energy, in a time period ΔT, in all wind speed range and the available energy considering that, in the same period, the wind speed $V=V_m$, that is: $x=1$. The portion of available energy in a speed interval [0 x] can be described as a cumulative distribution of available energy $E(x)$ defined by Eq. (4) and presented in Fig. 3.

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

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

$$K_E = \frac{\langle V^3\rangle}{V_m^3} = \int_0^\infty f(x)x^3dx \tag{3}$$

$$E(x) = \int_0^x D(x)dx \rightarrow \Delta E = E(x_2) - E(x_1) = \int_{x_1}^{x_2} D(x)dx \tag{4}$$

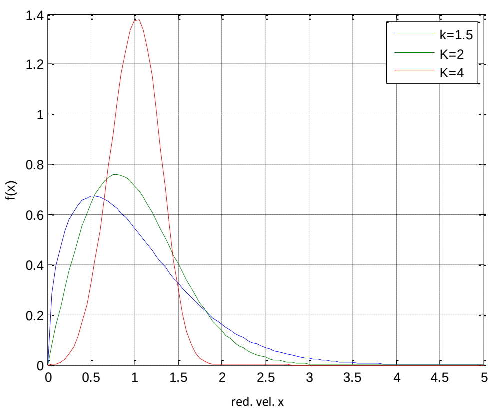

Figure 1. Wind speed frequency curve.

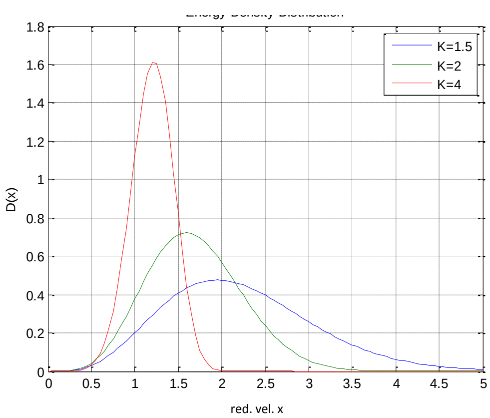

Figure 2. Energy density distribution.

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Figure 4 shows how K_E varies with k. It can be noted that K_E decreases as k increases. For the northeast coast where $k=4$, the energy available is 46% and 65% of the corresponding $k=1.5$ *and* $k=2$, respectively, for equal average wind speeds in the two regimes.

Another variable required for wind energy analysis is the available wind power, P_{avail}, at the height of the rotor shaft for an area corresponding to the area swept by the rotor, given by Eq. (5). Due to the high heights of the lift towers, fabricated today with more than 100 m, the value of the air density ρ shows a gradual decrease.

$$(x) \quad - \quad x \qquad (5)$$

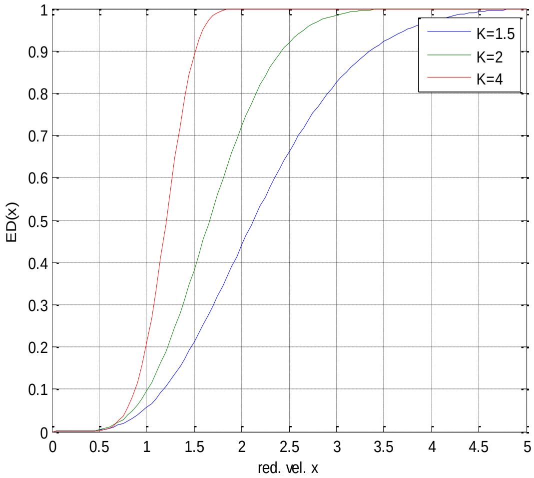

Figure 3. Cumulative available energy distribution.

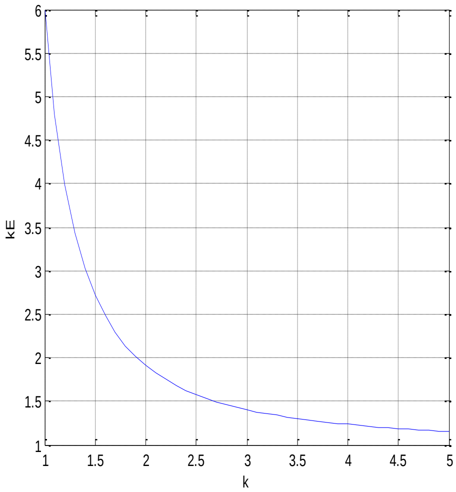

Figure 4. The energy pattern factor as a function of *k*.

Figure 2 clearly shows the wind speed range that holds a high energy content and the peak of the curve for $k=1.5$ is given for $x=1.8$. For this value, with $k=4$, this distribution tends to nullify its energy content. It is concluded that, for $k=1.5$, the largest portion of the available energy is concentrated in higher winds.

3. CAPACITY FACTOR (CF)

The *CF* value depends on the electrical power generated by the WECS already established by the manufacturer from open field tests resulting in the power curve versus wind speed. In this case, there are two operating range: sub rated and rated speed ranges [x_{in} x_r] and [x_r x_{out}], respectively, as shown in Fig. 5 (Burton *et al.*, 2001). The value of x_r is the reduced rated wind speed and defines the limit between two parcels of energy generated. The speed x_{in} specifies the initial operation speed at which the generator starts generating power, while x_{out} is the maximum operating speed, or a security limit at which the generator is turned off. Typically, the cut-in speed lies between 2 and 4 m/s, the rated speed is between 11 and 14 m/s and cut-out speed between 20 and 25 m/s. From Fig. 5, the energy generated is composed of two parcels with values that depend primarily on the value of x_r and the rated power P_r.

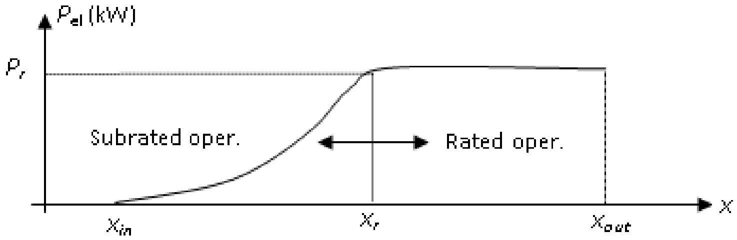

Figure 5. Generated electric power as a function of reduced wind speed.

As it was already explained, the *CF* is the relation between the generated energy and the energy to be generated by the wind turbine, at the same period, at rated operating condition.

$$\frac{}{} \quad \frac{}{} \quad \frac{}{} \qquad (6)$$

Therefore, the greater x_r the greater the amount of energy generated in sub rated operation and hence the lesser the value of *CF*. In contrast, the efficiency of the conversion system is greater in the sub rated power range, since the electrical power is controlled by blade pitch in the rated power range which reduces the aerodynamic performance of the rotor. It is concluded that the improvement of the *CF* does not necessarily increase the efficiency of the system. However, the *CF* can be increased by reducing x_r that can be made by reducing P_r or increasing parameters such as rotor diameter and average wind speed.

Considering the issue of the *CF* value from the energy density point of view, as shown in Fig. 2, it can be found that if $x_r \geq . 8$ then there is no generation in rated power operation for turbines installed in the northeastern coast which means low *CF* value. Similarly, in Northern Europe where $k=2$, about 40% of wind energy is available for $x_r \geq . 8$ which would result in a high *CF* value. Considering that the average wind speed is the same for both situations, the European optimized design to be applied to the northeastern coast should represent a lower *CF* value even though its energy conversion capacity remained unchanged.

4. PRODUCTION IN HIGH PERFORMANCE WIND TURBINES

VSVP wind turbine can operate under maximum aerodynamic performance throughout the sub rated operating range, that is (x) $_x$., where C_p is the rotor power coefficient defined by the C_p versus tip speed ratio curve. The power generated by the wind turbine is given by:

$$P_g(x) = \eta_{el-mec}(x) C_p(x) \tfrac{1}{2} \rho A V_m^3 x^3 \tag{7}$$

Where $\eta_{el\text{-}mec}$ represents the electromechanical conversion efficiency and is related to mechanical losses due to friction (in the bearings and multiplier) and the holmic losses in the generator, transformer and AC-DC-AC converters, being approximately constant throughout the operating range. Due to the random nature of the wind, the power generated has a distribution similar to the wind speed frequency given by Eq. (1). Thus, the differential of generated energy is:

$$(x) \quad x \tag{8}$$

where ΔT is the time interval. For sub rated power operating range $x \in [x_{in}\ x_r]$ and rated power range $x \in [x_r\ x_{out}]$, then the generated energy in all the operating range is given by:

$$\begin{aligned} E_g &= \int_{x_{in}}^{x_r} P_g \Delta T\, f(x)dx + \int_{x_r}^{x_{out}} P_g \Delta T\, f(x)dx = \\ &\int_{x_{in}}^{x_r} \eta_{el-mec}(x) C_p(x) \tfrac{1}{2} \rho A V_m^3 x^3\, \Delta T\, f(x)dx + P_r \Delta T \int_{x_r}^{x_{out}} f(x)dx \end{aligned} \tag{9}$$

The rated power P_r shown in Fig. 5, for (x) $_x$, is:

$$P_r = \eta_{el-mec}(x) C_{p\max} \tfrac{1}{2} \rho A V_m^3 x_r^3 \tag{10}$$

According to Eqs. (9) and (10), E_g can be defined from Weibull functions, given in Eqs. (1) and (2):

$$E_g = P_r \Delta T \left(\frac{K_E}{x_r^3} \int_{x_{in}}^{x_r} D(x)dx + \int_{x_r}^{x_{out}} f(x)dx \right) \tag{11}$$

Therefore from Eq. (6):

$$CF = \frac{K_E}{x_r^3} \int_{x_{in}}^{xr} D(x)dx + \int_{x_r}^{x_{out}} f(x)dx = CF_1 + CF_2 \tag{12}$$

where the terms CF_1 and CF_2 can be analyzed based only on Weibull distributions, through the shape parameter k and the parameters x_r, x_{in} and x_{out}. With this, the variable of the problem becomes x_r. From Fig. 5, it is concluded that the *CF* value tends to 100% when x_r tends to zero, which however makes no sense, since this would result in a very low rated power wind turbine. On the other hand, the use of high x_r values results in a system that generates low energy in sub rated operation resulting in low *CF* and a high cost system, since all its components would be dimensioned for high power. The optimized design of the wind turbine, based on *CF*, should consider the aspect of cost per kWh generated where there is a compromise between energy production and the cost of WECS. Figure 6 shows how the *CF* value

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varies as a function x_r according to Eq. (12), for values of $x_{in}=0.5$ and $x_{out}=3.0$. Regardless of the wind regime, increasing the value of x_r reduces the *CF* value even though it represents a variation in the rated power. In another way, the reduction in the ratio CF_2/CF_1, due to the x_r increased, reduces the *CF* value. Moreover, changes in *k* also produces changes in the *CF* value.

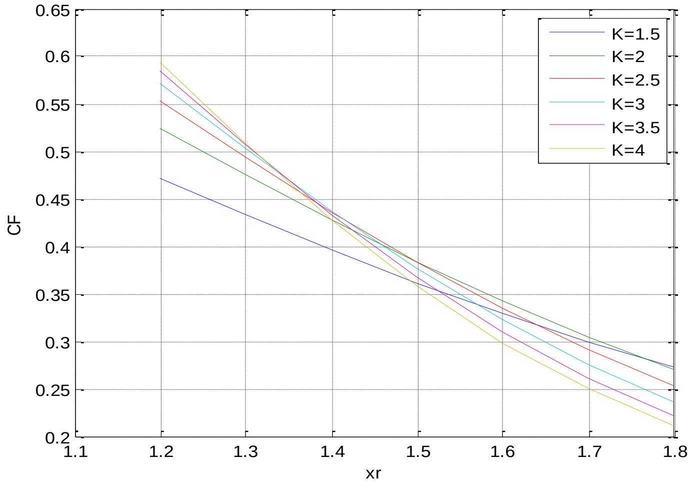

Figure 6. *CF* value as a function of x_r for different values of *k*.

5. WIND TURBINE RECONFIGURATION

The WECS to be installed under different wind project conditions fail to produce optimal power, and as a result, reconfiguration is needed.

The optimization of a wind turbine is first of all a matter of technological development that requires time, considerable manpower and financial resources. Thus, for example, its mechanical resistance meets the criteria of international standards that establish parameters according to wind classes (IEC, 2006).

The optimized model, therefore, is linked to certain design conditions defined previously (Burton *et al.*, 2008). Among the design parameters, the rated power is related to a set of electrical/electronic components representing a significant portion of the total cost, and as a result a change in P_r becomes infeasible. The reconfiguration problem involves choosing a new x_r value-based on the production of generated energy in a given period ΔT.

From Fig. 6, the new x_r value can be obtained as long as the design value x_{rd} defined by the manufacturer is known, from the value of $V_r=x_rV_m$. On the other hand, when *CF* is plotted as a *k* function, as shown in Fig. 7, it can be verified that for each x_r value, there is a peak value for *CF* for a given value of *k*. For $x_r=1.6$, for example, the maximum *CF* occurs for $k=2$, which corresponds to the European regime. Likewise, in the northeastern coast, *CF* shows a peak for $x_r=1.3$.

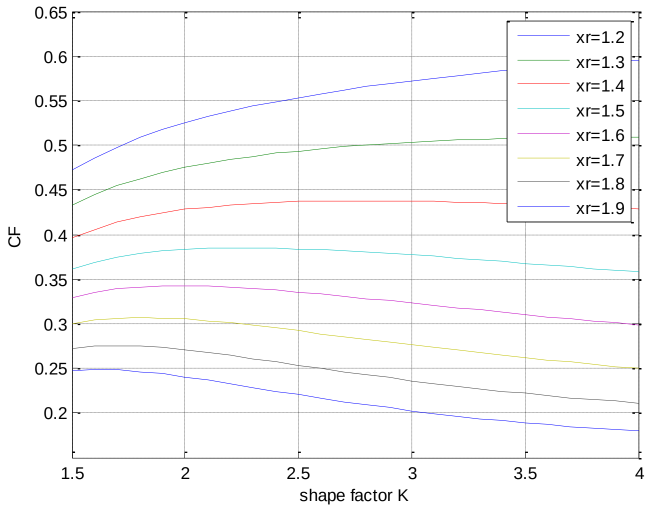

Figure 7. Variation of the *CF* parameter versus *k*.

To solve the reconfiguration problem, some manufacturers have chosen to increase the rotor diameter in order to broaden the swept area A, and also to increase the tower height in turn increases the mean wind velocity due to wind shear effect. The best option is defined based on an analysis of the costs involved. Both the increase in diameter and the tower height enables the rated power P_r to be achieved with lower x_r values. Given that these changes do not alter the aerodynamic performance or the conversion efficiency, it is possible to define the condition for reconfiguration based on Eq. (10).

$$P_r = cte \;\; \Rightarrow \left(A V_m^3 x_r^3\right)_{des} = \left(A V_m^3 x_r^3\right)_{new} \tag{13}$$

Where the design value $(V_r = V_m\, x_r)_{des}$ is defined by the manufacturer while the value $(x_r)_{new}$ would be defined from reconfiguration based on Eq. (13), for the local V_m. If the reconfiguration is based on increasing the rotor diameter, the new value would be given by:

$$D_{new} = D_d \sqrt{\left(\frac{x_{rd}\; V_{md}}{x_r\;\; V_m}\right)^3} \tag{14}$$

On the other hand, if the change to be made is to increase the tower, then a new height that would provide a new average wind speed. The value is:

$$\frac{x}{x} \tag{15}$$

6. RESULTS

Initially, it is considered that the WECS was projected to operate with a rated wind speed of V_r.=14 m/s. In Europe, with $k=2$, the optimal operation with $x_r=1.6$ would be verified with V_m=8.75 m/s, resulting into $CF=34\%$. For average wind speed higher than 8.75 m/s the x_r value would decrease and in turn increases CF. Assuming a reduction in V_m to 7.5 m/s, $x_r=1.87$ would decrease CF from 34% to 25% and in a generated energy loss in an order of 25%.

In the Northeastern coast, with $k=4$, for V_m=8.75 m/s and $x_r=1.6$, CF would decrease to 30% which would lead to a reduction of 12% in the generated energy. For V_m=7.5 m/s and $x_r=1.87$, CF=18% with a reduction of almost 50% in the generated energy. In this case, the damage caused in the production of energy is much higher than in Europe. Therefore, in the Northeast case, it is necessary to reduce the value of V_r so as to decrease the value of x_r and, thus, increase CF. Taking, for example, V_r=11.5 m/s and assuming V_m=8.75 m/s this would lead to $x_r=1.3$ resulting in CF=51%.

Making a reconfiguration of the system by increasing the rotor diameter such that the rated power doesn't become affected by reducing V_r from 14 m/s to 11.5 m/s, an increase in the rotor diameter by 34% would be needed, but on the other hand, CF would go from 34% to 51% representing an increase by 50% in energy production. Therefore, reconfiguration is shown to be quite an economically attractive tool, when the WECS designed with high values of V_r are installed in places like the Northeast where the k value is high.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Ackermann, T., 2005. *Wind Power in Power Systems*. John Wiley & Sons, England, 1st edition.
Boccard, N., 2009. "Capacity factor of wind power realized values vs. estimates". *Energy Policy*, Vol. 37, pp. 2679-2688.
Burton, T., Sharpe, D., Jenkis, N. and Bossanyi, E., 2001. *Wind Energy Handbook.* John Wiley & Sons, England.
Hau, E., 2006. *Wind Turbines - Fundamentals, Technologies, Application, Economics*. Springer. Germany, 2nd edition.
IEC 61400-2, 2006. "Wind turbines - Design requirements for small wind turbines". Geneva, Switzerland.
Lysen, E.H., 1983. *Introduction to Wind Energy.* SWD Publications. Netherland, 2nd edition.
Medeiros, A.L.R., Araújo, A.M. and Oliveira Filho, O.D.Q., 2011. "Wind Turbine Coupling Load Modeling". In *Proceedings of the 21st Brazilian Congress of Mechanical Engineering – COBEM2011.*Natal, Brazil.
Silva, G. R., 2003. *Características de Vento da Região Nordeste: análise, modelagem e aplicações para projetos de centrais eólicas.* MSc thesis, Federal Univesity of Pernambuco, Recife.

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