Proceedings of COBEM 2009
20th International Congress of Mechanical Engineering
November 15-20, 2009, Gramado, RS, Brazil
Copyright © 2009 by ABCM

ANALYSIS OF PRODUCTIVE EFFICIENCY LOSSES IN WIND ENERGY CONVERSION SYSTEMS (WECS)

Daniel E. Castro, daniel@plusengenharia.com.br
Centro Federal de Euducação Tecnológica de Minas Gerais- CEFET-MG, Av. Amazonas 7675, Nova Gameleira, Belo Horizonte, MG, Brasil.

Cláudio C. Pellegrini, pelle@ufsj.edu.br
Universidade Federal de São João Del Rey- UFSJ, Pça Frei Orlando 170, São João del Rey, MG, Brasil.

Alexandre Heringer Lisboa, ahlisboa@cemig.com.br
CEMIG, Av. Barbacena, Belo Horizonte, MG, Brasil.

Shirley Mota Pedreira, shirley_mota@bol.com.br
Centro Federal de Euducação Tecnológica de Minas Gerais- CEFET-MG, Av. Amazonas 7675, Nova Gameleira, Belo Horizonte, MG, Brasil.

Abstract. *The increasing demand for renewable energy sources joined to the increase in the energy consumption of the last decades and the higher quality requirements of the supplied energy are the basic aspects to be considered for the energy generation in the next years. The wind energy is becoming one of the more attractive options. Some positive points such as its low environmental impact and the use of renewable resources make countries like USA and many European Countries to invest in this energy source. There are, however, critical points that must be analyzed as the impact of the variability in the generation due to climatic oscillations and the high operational costs due to maintenance of the different components of the wind generation systems that increase significantly with the running time and can lead to make economically impracticable the operation of this type of power plants. This work aims to develop a method to evaluate the productive efficiency of wind energy generation systems considering aspects like the incidence of winds (probabilistic prospection) as well as operational aspects (maintenance, monitoring and inspection). The concept of Global Equipment Efficiency or OEE (Overall Equipment Efficiency) developed by the JIPM (Japan Union of Scientists and Engineers) will be used. This concept was developed to measure the efficiency losses in productive systems due to breakdowns, low operation speeds and poor quality. One of the primary objectives of this work is to develop a methodology to evaluate the global losses of the wind generation systems and to optimize maintenance processes considering low wind incidence time periods to make preventive maintenance allowing to maximize the productivity of the aeolian generation systems.*

Keywords*: wind power, maintenance, reliability, overall efficiency*

1. INTRODUCTION

The accelerated world-wide economic growth and the increasing modern society necessities to transform raw materials into products and services of more aggregate value demand higher capacities for energy generation and transmission. From all mentioned aspects the most important is related to environmental sustainability. This matter is being the pivotal question for the choice of future energy sources.

The climatic heating and the economical and political instability related to fossil oil resources are demanding a change in energy generation concepts and energy use. However all these aspects need to be observed considering too the availability of great amounts of energy in order to supply the increasing energy demand of the market. New energy sources need to be cheap and renewable in order to compete with conventional energy sources. One of the main inherent problems of wind energy production is related to variability that depends on season and characteristics of the installation place. These characteristic cannot be easily managed since it is not easy to store wind energy. Thus, management of wind energy systems must optimize the asset availability in periods with maximum wind incidence.

One of the most critical points in the operation of this type of energy systems is related to operational costs. Maintenance costs are, in general way, three times superior that maintenance costs for conventional energy generation systems. The goal of this work is to carry out a survey in order to analyze the availability and efficiency of wind energy production systems. Data of an existing real wind energy plant will be analyzed and processed in order to define the main factors influencing the global efficiency of wind energy generation systems.

2. **FACTORS THAT MODIFY THE WIND DISTRIBUTION**

The earth's atmosphere may be considered a huge thermal engine, powered by the Sun, where the air masses are transported by the existing temperature differences. Solar irradiation reaches a maximum near the equator, and decreases pole wards due to the spherical shape and the axis tilting of the planet. This creates a permanent equator-pole heat flux (sensible and latent) which tends to reduce the thermal energy excess near the equator. The process originates the currents known as global circulation of the wind.

Superimposed to this global circulation, there exist a number of local winds originated by different processes, amongst which two are worth of note for our purposes: the land-sea breeze and the mountain-valley breeze. The land-sea breeze is a periodic wind (24 hour cycle) observed in costal regions and, less intensely, near large lakes and rivers. In those regions the land gets warmer than the water during the day, due to its smaller heat capacity, originating an ascending column of warm air, which causes cool and humid air from over the water to flow in and replace it. That is the sea breeze. At night the process is reverted, because land cools more rapidly than water. The wind originated, known as land breeze, are less intense than the sea breeze, due to surface roughness associated with vegetation and topographic variations among other factors. “Fig. 1” (Stull, 1997) illustrates the sea breeze circulation.

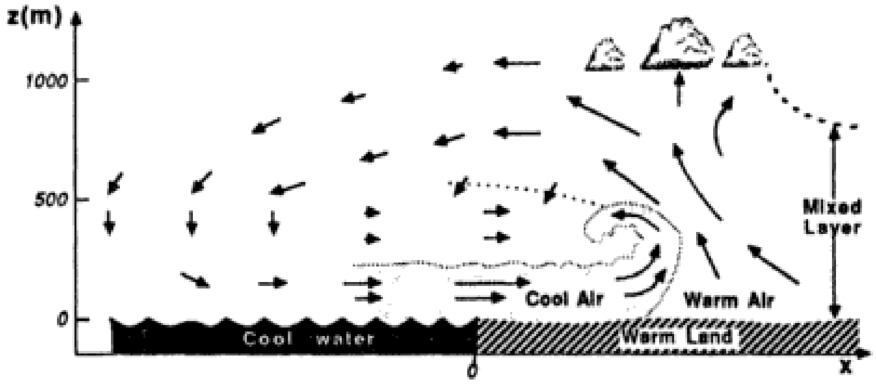

Figure 1 – Idealized sea breeze (after Stull, 1997)

In mountainous regions many local winds are also observed, most of them also generated by temperature differences but influenced by topographical aspects of the terrain. There are the so called drainage flows, which carry cool, heavier air down the slopes during the night, and the anabatic winds which bring warmer, lighter air up the hills during the day (fig. 2, after Stull, 1997).

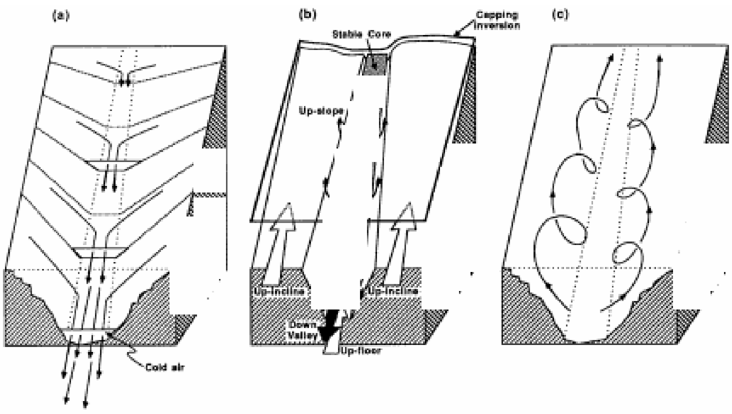

Figure 2 – Local mountain circulations (after Stull, 1997). night (left); morning (centre); afternoon (right)

Another possible source of variation for the wind is friction with the underlying surface. The decelerating effect of the friction forces plus its warming or cooling effect creates a “perturbed” region in the lower atmosphere known as the atmospheric boundary layer, where velocity goes to zero at the surface to values of the order of 10 m/s aloft. Depending on the terrain roughness, on the vertical distribution of temperature and moisture and on the prevailing large-scale atmospheric situation, the depth of the ABL can vary significantly. A typical value is 1 km.

Wind turbines work in the atmospheric boundary layer and suffer the influence of breezes and other geographical factors. Hence, a careful selection is needed to place wind turbines.

3- CHARACTERIZATION OF THE AVAILABLE ENERGY IN THE WIND

The available energy in the wind is in the form of kinetic energy due to air masses moving in the atmosphere. This energy can be determined by the following equation,

$$E = ½\, m\, v^2 \tag{1}$$

In this equation m is the air mass and v the air velocity.
The wind power on a control flow surface *F* can be calculated as the variation of the energy with the time,

$$Pot = dE/dt = ½\, [dm/dt]\, v^2 = ½\, \rho\, F\, v^3 \tag{2}$$

where ρ is the air density.

In order to calculate the amount of energy that can be obtained from a moving air mass passing through an installed impeller in an air flow can be used the approach of Betz (Gasch, 2007). In this model an ideal air flow (with no viscosity) with an initial velocity v_1 reaches the impeller with an air velocity v_2. "Fig. 3" shows the flow parameters used by this model (Gasch, 2007).

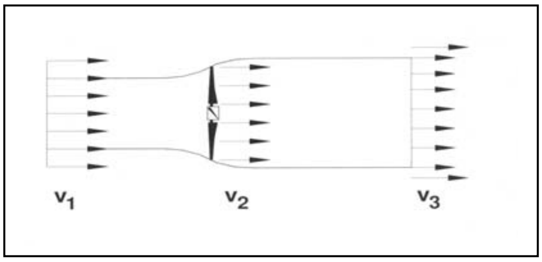

Figure 3 – Air flow according to Betz´s model

According to Betz´s model the power on the impeller can be calculated using the following equation,

$$Pot_{\ impeller} = ½\, \rho\, F\, v_1^3\, [\, ½\, (1+v_3/v_1)\, (1-v_3/v_1)^2] = ½\, \rho\, F\, v_1^3\ C_{p,} \tag{3}$$

The coefficient $C_{p,\ Betz}$ is defined as,

$$C_{p,Betz} =[\, ½\, (1+v_3/v_1)\, (1-v_3/v_1)^2] \tag{4}$$

The maximal value of $C_{p,Betz}$ = 0,59 is reached when v_3/v_1=3

That means that the maximal amount of energy on the impeller is approximately 60% of the available energy on the air mass flow. This model does not consider viscosity losses existing in the air flow passing through the impeller surfaces. In order to consider these additional losses a real efficiency factor $C_{p,\ real}$, (Gasch, 2007) must be introduced that depends on the type of airfoil used in the impeller, the number of impeller blades and the rate between maximal impeller tangential velocity and initial air velocity (v_1). "Fig. 4" shows the relationship between all these parameters and the variation of the real efficiency factor $C_{p,\ real.}$

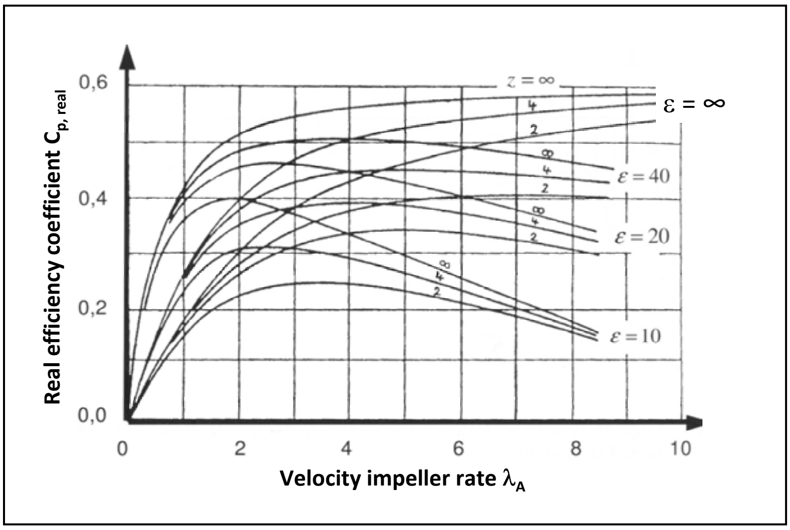

Figure 4 – Variation of the real efficiency impeller coefficient $C_{p, real}$

In this figure the parameter λ_A is the speed rate of the impeller defined as follow,

$$\lambda_A = \omega R / v_1 \tag{5}$$

Where ω is the angular velocity and R is the impeller radius. The parameter ε in figure 4 is the called glide rate of the airfoil defined as follow,

$$\varepsilon = (Lift\ force / Drag\ force)_{airfoil.} \tag{6}$$

It can be observed in figure 4 that the maximal real impeller efficiency depends on the aerodynamic performance of the airfoil (ε), the impeller radius (λ_A) and the number of blades used in the impeller (z). For airfoils showing good aerodynamic performance (ε ca. 40) and speed rates λ_A between 2,5 to 6 can be achieved real impeller efficiencies between 0,45 and 0,50 depending on the number of blades of the impeller. It can be concluded that the maximal real power on the impeller lies between 45% and 50% of the available energy in the air masses considering all the real aerodynamic losses in the air flow circulating trough the impeller.

4- INFLUENCE OF ELECTRO-MECHANICAL FACTORES TO TRANSFORM THE ENERGY OF THE IMPELLER INTO ELECTRICITY

The most common application of WECS is the generation of electricity. In order to transform the mechanical energy of the impeller into electricity different electro-mechanical components are needed like gear transmission systems, electrical generators, breaking systems of the impeller, etc. All these components consume part of the mechanical energy available on the impeller due to energy losses originated in frictional processes of mechanical components, inductive losses of electrical components and electrical losses due to resistive effects in the different electrical conduits of the generators and other electrical components of the system.

In order to evaluate these energy losses a testing bench was implemented in LAER (Petry et al, 2006), Laboratory for Renewing Energies of NUTEMA using a small electrical generator used in small wind power systems. The results of these tests are showed in “Fig. 5”.

As observed in “Fig. 5” mechanical losses are much lower than electrical losses considering the whole energy losses in the generator. Another important result is that all observed electro-mechanical losses do increase significantly with the rotation velocity of the impeller. That represents a serious limit for WECS because discourage the construction of high speed wind power systems. The relation between the available impeller energy and the power of the generator (see Figure 5) indicates that for small electrical generators the whole losses due to transformation from mechanical into electrical energy can consume up to 80% of the available impeller energy. These data can not be directly used to evaluate energy losses in all kind of WECS because were obtained only in small sized wind system generators. But the results can alert all users of this kind of power systems because the electro-mechanical transformation losses can consume more than 50% of the mechanical energy available in the impeller. More detailed laboratory tests are needed in order to define with more precision these energy losses in wind power conversion systems.

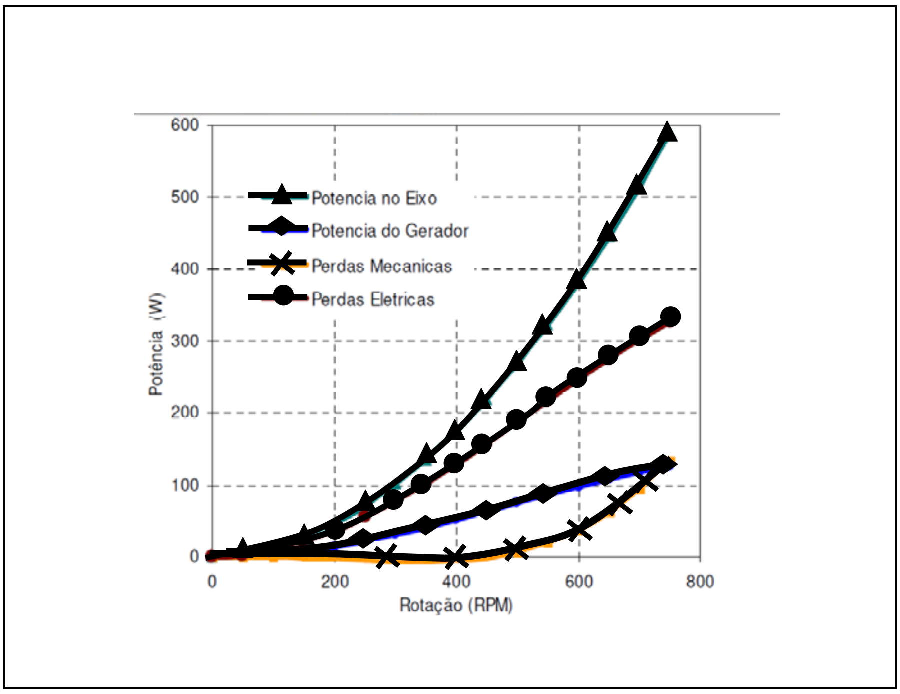

Figure 5 – Comparative analysis of energy losses in a small sized electrical generator (Petry, 2006)

5-INFLUENCE OF OPERATIONAL FACTORS IN THE ENERGETIC EFFICIENCY OF WECS

Despite aerodynamic and electro-mechanical transformation losses are very significant as stated in the last sections it can not be guaranteed that all electrical power generated in WECS can be delivered with maximal efficiency to the electric distribution system. According the experience of several WECS actually operating in different countries in the world it can be observed that different operational factors can still limit their energetic efficiency. One of the most important operational factors is linked to maintenance problems. Unexpected breakdowns and high maintenance costs can inhibit the operational success of this kind of power systems. “Fig. 6” shows the development of different operational costs of WECS during their useful life (Gasch, 2007),

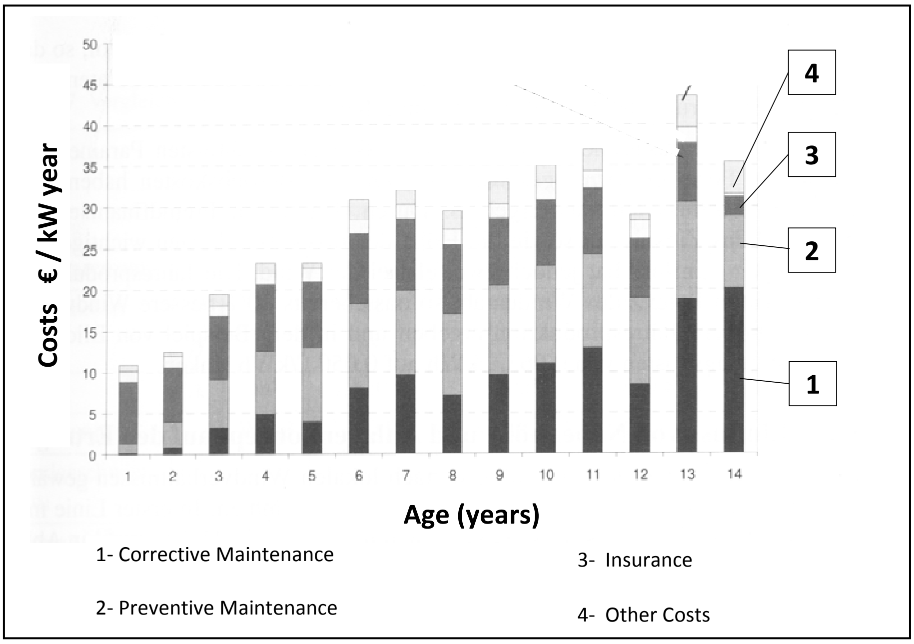

Figure 6 – Operational annual costs of Wind Power Conversion Systems (Gasch, 2007)

In “Fig. 6” can be observed that after 10 year the operational WECS costs quadruplicates. It must be pointed out that the most important cost is due to corrective maintenance activities (unexpected or unscheduled maintenance), as observed in “Fig. 6”.

In order to evaluate more accurately the impact of operational factors in WECS the operational data of the pilot WEC plant of Morro do Camelinho operated by CEMIG (Energy Company of Minas Gerais) will be analyzed. This Power Plant is located in Serra do Espinhaço municipal district of Gouveia in Minas Gerais State. The WEC Plant of Morro do Camelinho was the first Brazilian experience in such power generation plants. The principal aim of this plant was to serve as laboratory with no commercial purposes. The pilot plant is composed by four wind power units TW250 manufactured by the German company Tacke Windtechnick. Each unit has a nominal capacity of 250 kW of horizontal axle impeller type. The rotor has 3 blades and a diameter of 26 m using stall power control. The unit is mounted on a 30 m height conic steel tower.

The electric generator is of three-phase and asynchronous type (8/6 poles) with a power capacity 80/250 kW operating at rotation velocities between 900 to 1200 rpm respectively. The pilot WEC plant of Camelinho is fully automatic and is fitted with telemetry control of start and stop of turbines, overcharge and undercharge control, frequency failure control and vibration control among other parameter summarizing more than 50 different registers.

The electricity generated by the Power Plant is of 380 V and 60 Hz elevated to 13, 8 kV and transmitted to a 1 MW substation built near the plant. From this point the electricity is elevated once again to 34, 5 kV and connected to the distribution net of Paraúna-Gouveia. The Plant of Morro do Camelinho was installed at 1.300 m height at 240 km from Belo Horizonte city. The most common winds are from the high pressure zone localized in the Atlantic Ocean oriented predominantly from the east (66%). In table 1 is showed the wind distribution intensities measured on each wind power unit of the plant.

Table 1 – Wind frequency distribution (%) measured on each power unit of the Plant (CEMIG, 1998)

Wind velocity frequency classes (m/s)	**Wind Power Unit**			
	1	**2**	**3**	**4**
3 - 4	7,4	5,6	9,5	4,7
4 - 5	22,3	25,2	26,4	24,8
5 - 6	21,8	22,6	23,9	21,5
6 - 7	17,8	18,2	17,2	17,7
7 - 8	13,1	12,1	10,9	12,7
8 - 9	8,8	8,4	6,7	8,6
9 - 10	5,0	4,5	3,1	5,3
10 - 11	2,4	1,9	1,3	2,6
11 - 12	0,6	0,7	0,5	1,1
12 - 13	0,3	0,3	0,1	0,4
13 - 14	0,1	0,1	0,1	0,2
Mean Veloc. (m/s)	**6,23**	**6,17**	**5,88**	**6,31**

5.1- Quantification of operational efficiency using the Overall Equipment Efficiency concept (OEE)

One of the most serious problems to quantify the efficiency of production system is to consider all possible losses existing during the production processes. JUSE (Japan Union of Scientists and Engineers) created a maintenance strategy called TPM (Total Productive Maintenance) that consider three types of production losses,

-**Unexpected breakdowns losses**
-**Reduced production velocities losses**
-**Quality losses**

In order to quantify these three types of production losses JUSE created a global parameter called OEE (Overall Equipment Efficiency) (Hansen, 2002) calculated as follow,

$$OEE = \text{Availability Factor (A) x Velocity Factor (B) x Quality Factor (C)} \quad (7)$$

Availability Factor (A): This factor is calculated based on calendar time and all kind of expected and unexpected standstills of a production process, like maintenance programmed activities, unexpected breakdowns, operational standstills. This factor is calculated as follow,

$$A = \frac{\text{Calendar Time – Standstill time}}{\text{Calendar Time}} \quad (8)$$

Velocity Factor (B): This parameter is calculated based on the effective operational time and a standard production time (time to produce a unit o product),

$$B = \frac{\text{Standard time x } N^o \text{ of produced products}}{\text{Calendar Time – Standstill time}} \quad (9)$$

Quality Factor (C): This factor evaluates the production losses due to low quality standard of production. The quality factor is calculated as follow,

$$C = \frac{N^o \text{ produced products} - N^o \text{ reproved products}}{N^o \text{ produced products}} \quad (10)$$

5.2- OEE evaluation of the Morro do Camelinho WECS

The aim of this section is to evaluate the global operational efficiency of the Morro do Camelinho WECS using the OEE concept.

In Tab. 2 are showed the operational data measured on the four power units of the Camelinho Plant by CEMIG during the period August 1994 – June 1997. Column (I) of Tab. 2 shows the total production of the four power units in kW. The second column (II) shows the effective production hours that means, the real productive hours discounting all types of standstills of the four power units. Column (III) represents the available operating hours that are calculated as the calendar monthly hours minus the calmness time. The calmness time are the hours with the lowest wind velocities (lower than 3, 33 m/s), according to CEMIG information. Under such wind condition the operation of the power units is stopped. The standard time was calculated as the quotient between the effective production time (column II) and the total produced energy (column I). The standard time calculated using the data of CEMIG was 3,57 hr/kW. This parameter was used to calculate the velocity factor [B].

Based on these data the three OEE factors were calculated using following relationships,

A = Column (II) / Column (III) (11)

B = Standard Time (3, 57 hr/kW) x Column (I) / Column (II) (12)

C = 1 (quality losses were not considered in this approach)

OEE = A x B x C (13)

Table 2 – Operational data of Morro do Camelinho WECS (CEMIG, 1998) and OEE results

Month	(I) Total production KW	(II) Effective production time (hr)	Calendar time (hr)	Calmness rate [%]	(III) Available time (hr)	(IV) Standard Time [hr/KW]	Availability Factor [A]	Velocity Factor [B]	Quality Factor [C]	OEE = AxBxC
aug94	28,82	209,75	744,00	6,70	659,44	7,28	0,32	0,49	1,00	0,16
sep94	133,34	610,75	720,00	9,00	622,44	4,58	0,98	0,78	1,00	0,77
oct94	127,70	575,00	744,00	13,60	610,68	4,50	0,94	0,79	1,00	0,75
nov94	43,62	307,00	720,00	9,60	618,34	7,04	0,50	0,51	1,00	0,25
dez94	12,70	88,75	744,00	18,30	577,46	6,99	0,15	0,51	1,00	0,08
jan95	12,74	190,00	744,00	12,40	619,16	14,92	0,31	0,24	1,00	0,07
fev95	24,37	248,25	672,00	13,50	552,22	10,19	0,45	0,35	1,00	0,16
mar95	33,25	245,00	744,00	13,80	609,26	7,37	0,40	0,48	1,00	0,19
apr95	0,00	0,00	720,00	11,80	603,29		0,00		1,00	
mai95	15,30	196,00	744,00	17,04	586,36	12,81	0,33	0,28	1,00	0,09
jun95	46,62	373,25	720,00	13,50	591,66	8,01	0,63	0,45	1,00	0,28
jul95	97,61	485,25	744,00	9,60	638,95	4,97	0,76	0,72	1,00	0,55
aug95	90,65	461,00	744,00	6,70	659,44	5,09	0,70	0,70	1,00	0,49
sep95	121,39	433,75	720,00	9,00	622,44	3,57	0,70	1,00	1,00	0,70
oct95	56,23	366,00	744,00	13,60	610,68	6,51	0,60	0,55	1,00	0,33
nov95	56,15	351,50	720,00	9,60	618,34	6,26	0,57	0,57	1,00	0,32
dez95	56,32	377,50	744,00	18,30	577,46	6,70	0,65	0,53	1,00	0,35
jan96	42,30	357,75	744,00	12,40	619,16	8,46	0,58	0,42	1,00	0,24
fev96	38,04	272,25	696,00	13,50	571,94	7,16	0,48	0,50	1,00	0,24
mar96	46,20	438,00	744,00	13,80	609,26	9,48	0,72	0,38	1,00	0,27
apr96	75,16	502,50	720,00	11,80	603,29	6,69	0,83	0,53	1,00	0,45
mai96	38,93	405,50	744,00	17,04	586,36	10,42	0,69	0,34	1,00	0,24
jun96	68,19	421,50	720,00	13,50	591,66	6,18	0,71	0,58	1,00	0,41
jul96	61,23	483,75	744,00	9,60	638,95	7,90	0,76	0,45	1,00	0,34
aug96	57,93	207,00	744,00	6,70	659,44	3,57	0,31	1,00	1,00	0,31
sep96	104,71	467,00	720,00	9,00	622,44	4,46	0,75	0,80	1,00	0,60
oct96	85,74	542,25	744,00	13,60	610,68	6,32	0,89	0,57	1,00	0,50
nov96	128,00	569,50	720,00	9,60	618,34	4,45	0,92	0,80	1,00	0,74
dez96	52,98	547,75	744,00	18,30	577,46	10,34	0,95	0,35	1,00	0,33
jan97	65,46	528,25	744,00	12,40	619,16	8,07	0,85	0,44	1,00	0,38
fev97	135,00	592,00	672,00	13,50	552,22	4,39	1,00	0,81	1,00	0,87
mar97	122,00	611,50	744,00	13,80	609,26	5,01	1,00	0,71	1,00	0,72
apr97	80,88	574,25	720,00	11,80	603,29	7,10	0,95	0,50	1,00	0,48
mai97	35,97	236,75	744,00	17,10	585,94	6,58	0,40	0,54	1,00	0,22
jun97	39,36	391,00	720,00	13,50	591,66	9,93	0,66	0,36	1,00	0,24
							Mean Values			
				Standard time:		3,57	0,64	0,56	1,00	0,39

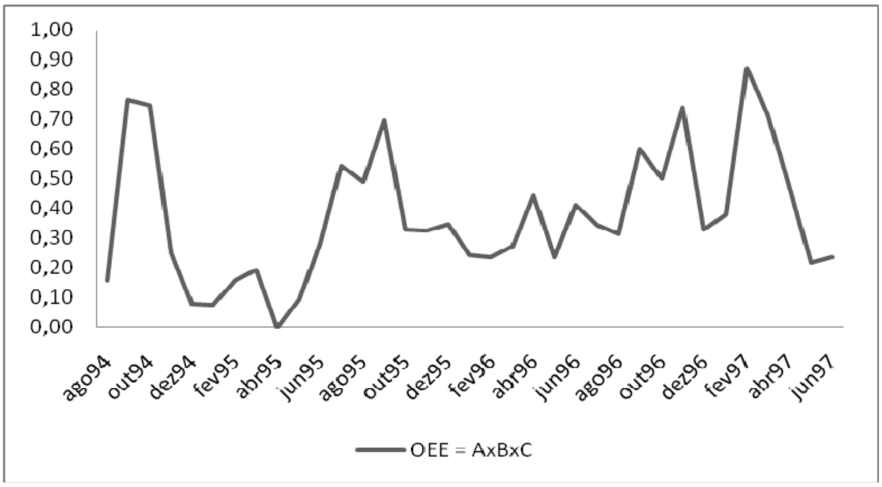

Figure 7 – OEE variation in Morro do Camelinho WECS

It can be observed in figure 7 that all calculated OEE values were under 80% during the whole analyzed period. The mean OEE value was 0, 39. It means that the mean value of all operational losses in Morro do Camelinho Plant were higher than 60% during this period of time. The mean availability factor (A) was 64%, the mean velocity factor (B) was 56%. Not quality losses were considered in this calculation due that low quality electricity need first to be defined in order to calculate these losses. According with JIPM world production standards OEE values of automatic production systems must lie between 85% and 90%.

The operational production losses observed in the pilot WECS of Morro do Camelinho are too much lower than the expected world class production standard established by JIPM. One of the main aspects to be analyzed in order to define root causes for the observed operational losses are inadequate maintenance procedures (Castro, 2006) that could be responsible for unexpected maintenance activities and low production velocities. Another important point to be analyzed is the influence of wind variation on low operational velocities.

6- Conclusions

Wind energy is one of the more promising energy sources for the future and its application is growing significantly in Europe and the United States. One aspect to be considered in this type of energy generation plants is the appropriate operational management since several generators are normally installed in the same site in order to maximize the use of kinetic energy of winds. This work showed that WECS undergo three main types of energy losses. The first loss type are energy losses due to aerodynamic factors reducing the available kinetic energy of air masses in approximately 60%. The second loss type is due to electro-mechanical losses originated in the transformation of mechanical energy of the impeller into electricity reducing further 50% the available energy. At least WECS show reduction of energetic efficiency due to operational factors like unexpected breakdowns and reduced operational velocities reducing once again the available energy in a factor of 60%. Thus, the energy that reaches the network does not surpass 15% to 20% of the available energy in air masses. From these three types of energy losses the only one which may be controlled during the WECS useful life are operational losses because the other two are defined in the project phase of the WECS-Plant and once erected the wind park is practically impossible their reduction. This work shows that operational WECS losses can be quantified by the parameter OEE (overall equipment efficiency) that describe energy losses due to standstill and low production velocities. This work will be continued in order to investigate root causes of operational losses, like maintenance management failures and unexpected wind intensity variations.

7. ACKNOWLEDGEMENTS

To CEMIG (Companhia Energética de Minas Gerais) for the provision of operational data of Morro do Camelinho WECS pilot Plant and to CNPQ (National Council of Research) for the financial support with Master’s fellowship.

8**. REFERENCES**

Castro, D. E.; Pinheiro, M. A., ‘’A simple but effective approach to control the performance of maintenance processes’’, MARCON 2006 Conference, Maintenance and Reliability Center - University of Tennessee - USA – 2006

Copyright © 2009 by ABCM

CEMIG, “Usina Eólio-Elétrica Experimental do Morro do Camelinho” - Relatório de Desempenho Operacional, 1998.
Dewi, Power Quality Measurement and Wind Turbine Operational Improvement at Cemig Morro do Camelinho Wind Farm, 1997.

Gaschr, Twele J., “Windkraftanlagen- Grundlagen, Entwurf, Planung und Betrieb” (equipamentos de geração de energia eólica: Conceitos básicos, Projeto, Planejamento e Operação), Editora B.G.Teubner, Wiesbaden 2007.

Hansen R. C., “Eficiência Global dos Equipamentos”, obra originalmente publicada sob o título Overall Equipment Effectiveness: a powerful production/maintenance tool for increased profits, Industrial Press Inc. – New York, 2002.

Leite, A.; Falcão D.; BORGES C., “Modelagem de Usinas Eólicas para Estudos de Confiabilidade”. *Revista Controle e Automação*, v.17n2, p.177-186, abril, maio e junho 2006.

Lobo, A.R., Alvarenga C.A., LISBOA A.H.. Usina Eólio-Elétrica Experimental do Morro do Camelinho - XIII SNPTEE. 1995. BRASIL.”Estudos sobre Aproveitamento de Energias Solar e Eólica em Minas Gerais” - Fase 1. 1987, CEMIG. “Levantamento de sítios eólicos em Minas Gerais” - Relatório Interno. 2001.

Petry, M. R., Konzen G., Ale V. J., “Ensaio Laboratorial para testes em bancada de geradores eólicos de pequeno porte”, IV Congresso Nacional de Engenharia Mecânica – CONEM 2006

Stull, R. B., “An Introduction to Boundary Layer Meteorology”, 6th ed., Dordrecht, Kluwer Ac. Publ., 670 pp, - 1997