THE DEVELOPMENT AND APPLICATION OF A MODEL FOR POWER OUTPUT FLUCTUATIONS IN A WIND PARK

A.I. Estanqueiro*, R. Aguiar*, J. Gil Saraiva*
Rui M.G. Castro, J.M. Ferreira de Jesus****

* INETI/DER, Az. Lameiros, 1699 Lisboa Codex, PORTUGAL.
Tel - 351 1 7162712 (ext-2725); Fax - 351 1 7160901; email - der@donald.ineti.pt
** INTERG / IST - Instituto da Energia Instituto Superior Técnico, Technical University of Lisbon
Av. Rovisco Pais, 1096 Lisboa Codex, PORTUGAL.
Tel - 351 1 808257; Fax - 351 1 8484235; email - rui@interg.pt

ABSTRACT: The study of the wind park's electric power output fluctuation effect on the a.c. System voltage and frequency regulation are a necessity when the connection of a Wind Park to the existing utility grid, specially a weak a.c. System, is intended.

The aim of this work in a global perspective is to analyse the electric power produced by a park in terms of stability of the grid and "quality" of the output. In this paper a non-linear model of a two WECS wind park, together with a model to generate correlated wind time series', is used to simulate the power output fluctuations. The time series' of the individual power generated by each WECS and the park's output series are analysed both in frequency and time domain.

1 - INTRODUCTION

The effect of WECS electric power output fluctuations in the existing a.c. system is a matter of great concern, since the utility distribution normal procedures concerning operation and planning do not generally take into account for independent power production [1,2].

This situation can be particularly serious for high levels of wind penetration or in weak grids, this being the case of Portugal where windy sites are sparsely populated, and in most of the cases have a very weak grid.

Therefore, the grid connection of wind parks with a considerable amount of installed power may pose some problems, not only to the utility grid management, but also to the wind park owner, since its production capacity may be limited by the utility due to stability problems or extreme voltage deviations.

The lack of an accurate tool which allows to assess the interaction between the wind parks and the utility grid leads to a peculiar situation: neither the utility is able to properly account for the perturbations induced by the wind parks in their system, nor the independent producers are able to predict the impact that the utility normal practises have in their installations.

Those are some aspects why an accurate model to simulate wind parks connection to the existing a.c. system is currently being developed. The ultimate aim of this work is to build a tool, to be used both by the utilities and by the wind park investors, which will allow an assessment of the impacts resulting from the connection of wind parks to the grid in selected windy locals.

In this first step only a two-turbine wind park was considered. Nevertheless, a considerable amount of work was spent in order to correctly model the spatial correlated wind in the different locations, the interaction between the turbine/generator groups inside the park and the utility grid near the wind park that can be disturbed by its performance.

2 - WIND PARK'S MODEL

If a dynamic time dependent model of a wind park is intended, some aspects have to be addressed, namely:

i) a spatial and time wind correlation method;
ii) a time-domain method to simulate the WECS and the electrical system;
iii) the computation of the electrical interaction between generators and transformers inside the park.

A wind model to generate correlated wind time series was developed to perform these studies [3]. The situation addressed here corresponds to a two side by side WECS wind park - thus wind turbines' wakes are not modelled.

The wind park's model is based in a dynamic WECS model developed previously. This WECS model results from the integration of a wind turbine's characteristic equation that accounts for the time variation of the shaft rotational speed and an existing induction generator model - developed in due time to apply to small hydro power plants [4] - that was adapted to perform the WECS typical behaviour with time variable torque [5,6].

The generator's model accounts for saturation effects of the induction generators thus including its non linear working range. The interaction between the two turbine/generator groups inside the power plant and the conditions at the interconnection busbar were established in order to model the electric power output.

2.1 - Wind Models

To achieve a dynamic model of a wind park, the knowledge of the simultaneous wind velocity time series, at the locations of the various turbines, is essential. This means not just using average wind velocities as input, but also the superimposed turbulence. This is required by the existence of phenomena associated with turbulence effects on the blade's loads, so on the turbine's power output, and even on the turbine's responses to electrical grid faults.

A preliminary wind model was developed, based on the so called "Shinozuka method", i.e. the generation of wind speed time series from the inverse FFT of a complex spectrum, whose real part is a wind power spectrum and the imaginary part is a random phase spectrum.

The current model is based on i) the Taylor hypothesis of "frozen" homogeneous turbulence; ii) the assumption that each size class of eddies is represented in the power spectrum by the energy at the frequency $f = L/v$, where L is the eddy size (along wind) and v the mean wind speed; and iii) the assumption that eddies with size less than the distance H between two certain sites will be too small to affect both of them at the same time - and therefore will bring a null average contribution to the cross-correlation.

Within these hypothesis, the Shinozuka method is used to generate cross-correlated wind speed series for any two places H apart taking the phase spectrum as equal for both places up to f=H/v, and random thereon [3]; the well-known "Davenport spectrum" shape was used as the power spectrum for both places with common average speeds at 10 m high of 7 m/s, and a roughness coefficient of 0.008.

Samples from the models stochastic wind series where taken as appropriate when yielding cross-correlations close to those estimated with exponential fits to field observations, with decay lengths of 200 m along-wind, and 50 m across-wind.

2.2 - WECS Model

To simulate the wind turbine performance the already mentioned time dependent model that uses as input the wind's velocity instantaneous value was used [5,6]. To describe the torque's characteristic of the turbine's rotor a characteristic equation that accounts for the shaft's rotational speed variation is used:

$$T_M(\Omega, V_0) = A(V_0)\Omega + B(V_0)$$

where $A(V_0)$ e $B(V_0)$ are wind's velocity dependent parameters, and Ω is the rotor's shaft rotational speed. This equation was found by applying numerical interpolation to the rotor's performance simulation results with an improved version of the PROPshaft code.

It has to be referred that the turbine's model doesn't include the aeroelastic effects on the blades neither the disk averaging effect. Thus the high frequency turbulence (aprox. over 1 - 2 Hz) present on the wind time series that is not filtered by the shaft and the generator will be present in the power output time series.

2.3 - Electric Equipment Models

Models have been developed to describe the behaviour of the different subsystems that constitute the electrical part of the system studied [4]. All models have been developed in the synchronous reference frame to avoid undesired dependence of rotor position.

The prediction of induction generator steady-state and transient performance requires proper account of saturation effects, thus a detailed model based on Von der Embse circuit theory was developed [7].

Each generator has its own reactive power compensation system, which has been sized in order that the admittance of the capacitor bank equals the slope of the linear part of the no-load magnetisation characteristic of the induction generator. This size was chosen as a result of previous studies in this domain [8] and complies to the Portuguese legislation.

The local loads were modelled as constant active and reactive power for the computation of initial conditions and as a constant impedance in the simulation studies. Both transformers, the feeder and the a.c. system were modelled also as constant impedance.

In order to obtain the initial conditions for the set of differential equations which accurately describe the system, a numerical model taking as input only the system parameters and the instantaneous wind speed was built. This technique enables the computation of the initial steady-state operating point through a modified power flow which takes into account the electro-mechanical characteristics of the turbine/generator groups to evaluate the rotor speed of each machine.

The WECS overall model was first presented in [5,6] and is now implemented in a software package named INDUSAT, which allows to perform several studies either in steady-state or transient conditions [9].

3 - TIME AND SPECTRAL ANALYSIS OF THE POWER OUTPUT FLUCTUATION SIMULATIONS

The wind park's model was applied to the topology represented in Fig.1. The system is basically composed by two side by side WECS equipped with squirrel cage induction generators, with reactive power compensation.

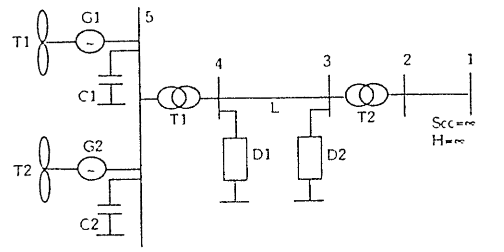

Fig. 1 - Grid's topology.

The generators are connected to a feeder through a step-up transformer, which feeds a local load. The interconnection substation is represented by another step-up transformer, which also has a local load connected to its low voltage side. Characteristics of the WECS and the grid simulated in this work can be found in reference [10].

The short-circuit power at the interconnection point was assumed to be 50 times the wind park rated power, thus the existing a.c. system is represented by a reactance with the appropriate value.

Using the wind park's model described above, some simulations were performed in order to obtain results in time domain. Moreover other type of studies have been carried out to assess some statistical characteristics of the power output (cross-correlation and standard deviation) as well as to examine the frequency domain results (Power Spectral Density - PSD) of the park's output.

The time domain output power series presented correspond to wind series with a cross correlation factor equal to 0.33. This value was selected as an example since it correspond to the typical cross wind distance for this kind of turbines (diameter -12 m).

Fig. 2, 3 and 4 show some results obtained in time domain. Fig. 2 depicts an sample of the correlated wind time series' (crosscor=0.33).

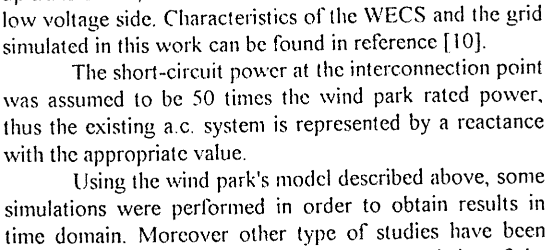

Fig. 2 - Wind times series (crosscor=0.33).

Fig. 3 and 4 display the power time series for each turbine (Fig.3) and the wind park's power output (Fig. 4).

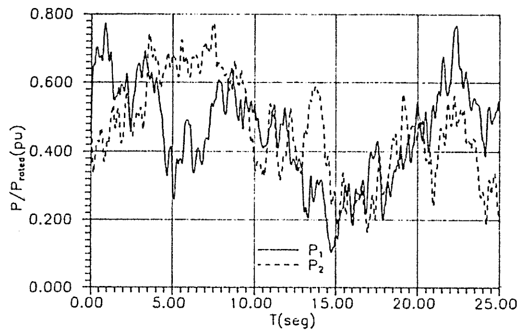

Fig. 3 - Turbine's power output (wind's crosscor=0.33).

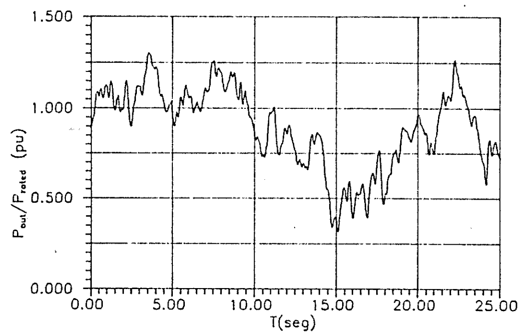

Fig. 4 - Park's power output (wind's crosscor=0.33).

Figures 5 and 6 deal with the statistical properties of the power produced by the wind park. In Fig. 5 it is represented the individual power series cross correlation factor between the two turbines against the cross correlation factor of the input wind time series.

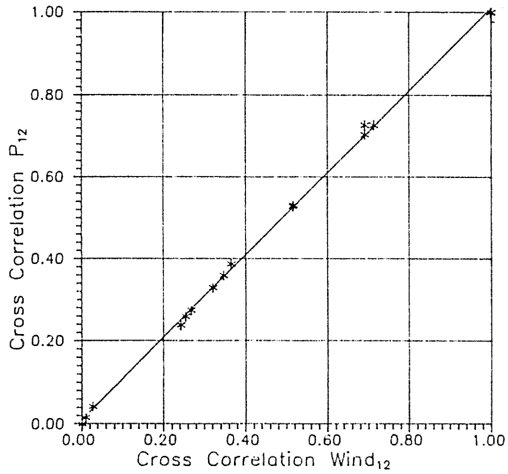

Fig. 5 - Park's power output crosscor vs. wind's crosscor.

In Fig. 6 the evolution of park's power output standard deviation versus the wind's cross correlation factor is plotted.

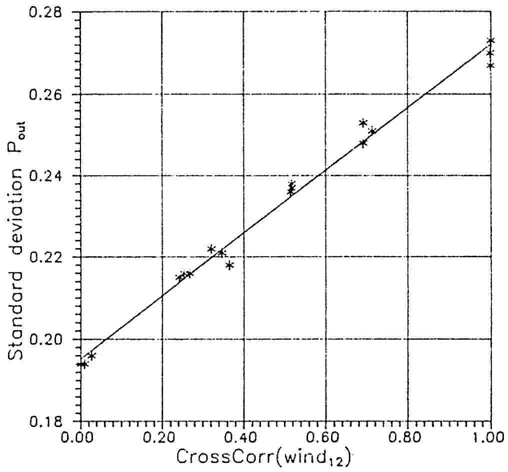

Fig. 6 - Park's power output standard deviation vs. wind's crosscor.

The power spectral density (PSD) of the park power output fluctuations' is plotted in Fig. 7. For each wind correlation factor the average PSD of the samples is computed and is presented. It may be seen that the lower curve corresponds to zero correlation and the upper curve to correlation factor equal to one (low frequency range).

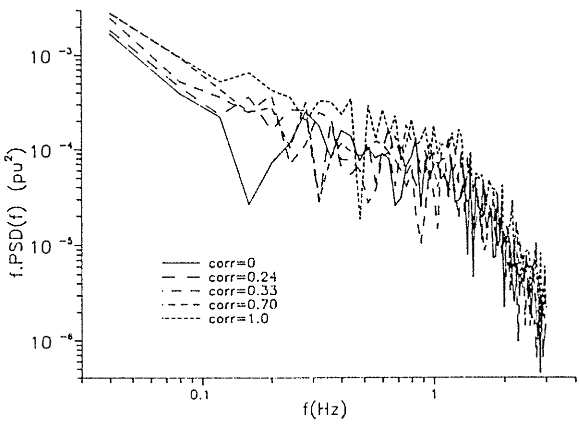

Fig. 7 - PSD of Park's Power Output fluctuations. The lower curve corresponds to wind's crosscor=0 and the upper curve to wind's crosscor=1.

Figure 8 corresponds to the power spectral densities of one sample of the power outputs of each turbine (P1, P2) and the park (Pout), for wind time series' cross correlation factor equal to 0.33.

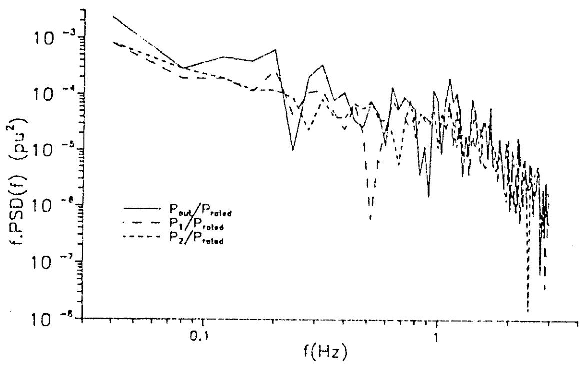

Fig. 8 - PSD of park's power output (solid line) and PSD of each turbine's power output (P1-dotted line, P2-dashed line).

The number of samples presented is not yet large enough to be representative of a stochastic process. However as shown in Fig. 5 and 6 the results dispersion is quite low.

Analysis of Fig. 5 shows a linear dependence between the two quantities in spite of the simulation model being non linear. In what concerns Fig. 6, it clearly shows an increase of the standard deviation with the wind's cross correlation factor.

Analysis of Figures 6 and 7 allows to conclude that an increase in the wind's cross correlation factor corresponds to a larger fluctuation in both the voltage and power output of the wind park. This result is in agreement with results pointed out by several authors [1, 2,11].

The N turbine smoothing effect is less obvious than expected in figure 8, which may partially be explained by the low number of turbines involved.

4 - CONCLUSIONS

The results presented agree quite well with results previously published on this subject (e.g. Beyer et al [1] and G. McNemey and R. Richardson [11]). The smoothing ("cancellation" of the turbine's individual high frequency fluctuations) in the park's power output fluctuations when the wind is uncorrelated is illustrated by Fig. 7 and 8. However attention must be paid to the space scale associated with this phenomena, since in this case only two turbines are involved and the distances between turbines are smaller (the frequency "cancellation" limit being higher as a consequence) than those of references [1,11].

Results show a dependence - that seems to be linear from the short number of simulated samples - on the wind's cross correlation factor, though a non linear model wind park is used.

The analysis of PSD of the park's output (Fig. 7 and 8) in the low frequency range brings up the idea that mean and standard deviation analysis should be complemented with both frequency and absolute value of extreme occurrences.

ACKNOWLEDGEMENTS

The authors want to thank to Dr. P. Christiansen by the valuable suggestions to the application of the wind model and to the procedure analysis of the stochastic output.

REFERENCES

[1] Beyer, H.G. et al; "Power Fluctuations from Geographically Diverse, Grid Coupled Wind Energy Conversion Systems; EWEC '89 Proc.; pp 306-310; Glasgow, 1989.

[2] Peltola, E. et al; "Simulations and Measurements on the Effect of a Wind Farm on the Local Grid", Paper D6 , EWEA Special Topic Conference '92 on the Potential of wind Farms, 1992

[3] Aguiar, R. et al "Uma abordagem espectral à Geração de Séries Correlacionadas de Vento" to be presented in "Congresso Ibérico de Energia Solar", Lisbon, April, 1993.

[4] Rui M.G. Castro, "Induction Generators: It's Use in Small Hydro Plants" (in Port.), MSc Thesis, IST., Lisbon, November 1988.

[5] Estanqueiro, A. I.; "Horizontal Axis Wind Turbines - A Behaviour's Model"., (in Port.) MSc Thesis, IST, Lisboa, April, 1991.

[6] Estanqueiro, A.I.; Ferreira de Jesus, J.M.; Gil Saraiva, J.A.; "WECS Unsteady Output Simulation", EWEC'91 Proc., pp 618-622. Amsterdam, 1991

[7] Ferreira de Jesus, J.M.; "A Model for Saturation in Induction Machines", IEEE Transactions on Energy Conversion,Vol EC-3, 1988

[8] Rui M.G. Castro, A. Eugénio Gomes, J.M. Ferreira de Jesus, "The Influence of Reactive Power Compensation in the Transient Behaviour of an Induction Generator", Proceedings IFAC, Seoul, August 1989.

[9] Rui M.G. Castro, J.M. Ferreira de Jesus, "INDUSAT Basic Reference Guide V1.0 - Software Package for WECS Simulation", Instituto Superior Técnico, Lisbon, January 1993.

[10] Estanqueiro, A.I, Ferreira de Jesus, J.M:, Lalos, D.; "Transient Behaviour of a WEC under Different Load Conditions", presented in "The potential for Small & Medium sized Wind Energy Applications in Mediterranean Countries" , Rhodes, Greece, 1992.

[11] McNemey, G. and Richardson, R., "The Statistical Smoothing of Power Delivered to Utilities by Multiple Wind Turbines"; IEEE/PES Winter Meeting paper 92 WM 024-0 EC,1992.

[12] Lipman; N.H. et al., "Fluctuations in the output of wind turbine clusters". Wind Engineering Vol. 4, no. 1, 1980

[13] Taylor, G. J.; "Power Quality Measurements on a 24 m Windmill", IEE Proceedings, Vol. 134, Pt. A, nº 5, May, 1987.

[14] Smedman, A.; "Effect of Wind Speed Fluctuations on the Power Output of the Wind turbine in Kalkugnen, Sweden", 4th International Symposium on Wind Energy systems, Sept., 1982

[15] Beyer, H. G. et al; "Fluctuations in the combined Power Output from Geographically Distributed Grid Coupled Wind Energy Conversion Systems - An analysis in the Frequency Domain", Wind Engineering Vol.14, nº3, 1990.

[16] W. E. Feero, W. B. Gish, "Overvoltages Caused by DSG Operation: Synchronous and Induction Generators", IEEE Transactions on Power Delivery, January 1986.

[17] R. Dugan, D. Rizy, "Electric Distribution Protection Problems Associated with the Interconnection of Small Dispersed Generation Devices", IEEE Transactions PAS, Vol. PAS-103, Nº6, June 1984.