* 2nd EECWE *
2nd East European Conference on Wind Engineering
Prague, 7 - 11 September 1998

MISTRAL
A tool to evaluate the impact of wind parks on electric distribution systems

Marques da Silva, Fernando[1];Estanqueiro, Ana I.[2];
Castro, Rui[3];Jesus, José F.[3] Saraiva, Jorge G.[1]
1- LNEC - NDA, Av. do Brasil 101, 1799 Lisboa Codex, Portugal
Tel : 351-1-8482131 ; Fx : 351-1-8463457 ; e-mail : fms@lnec.pt ; jsaraiva@lnec.pt
2- INETI - DER, Az. dos Lameiros, 1699 Lisboa Codex, Portugal
Tel : 351-1-7162712 ; Fx : 351-1-7163797; e-mail : ana.estanqueiro@ite.ineti.pt
3- INTERG, IST, Av. Rovisco Pais, 1096 Lisboa Codex, Portugal
Tel : 351-1-8484006 ; Fx : 351-1-8484235; e-mail : fjesus@hertz.utl.ist.pt

SUMMARY: MISTRAL is a project running within the NATO's Science for Stability Programme under the designation "Modelling Machine Interaction in a Wind Park with Regard to Stability and Regulation" and it's main goal is to allow the assessment of the wind power fluctuations effects on the electric power distribution grid as well as to evaluate the maximum wind power penetration value at a defined substation (or busbar) for no disturbance of consumers guaranteeing the overall power quality and support the design of the internal grid layout, reactive power compensation and protection systems. This assessment is to be performed in the feasibility phase of the wind park design.

1. INTRODUCION

The main objective of MISTRAL project is to develop a computational tool being able to assist both wind park designers and electric utilities in the impact evaluation of wind power electric generation on distribution systems.

To achieve this goal a consortium of institutions was established covering the areas involved on wind power chain from the potential assessment to the distribution, namely INTERG, within the Technical University of Lisbon for electrical models; INETI, the R&D state Institute of the Ministry of Industry and Energy, for electrical, atmospheric boundary layer (ABL), wind turbine, grid and overall models; LNEC, the state R&D Laboratory of the Ministry of Public Works, covering ABL and general flow models as well as wind tunnel tests over physical models; EDP, the mainland electric utility, and EDA, the Azores utility, for field work together with the other partners. Experimental work was performed by INETI, LNEC and EDA.

The project structure considers the establishment of numerical models to characterise the incoming wind, the machine interaction within the park, the development of a dynamic equivalent for the park, and the effects of wind power on the A.C. regulation system with particular emphasis on weak systems. The models developed within MISTRAL assemble all this parts and are being validated through field measurements at the S. Jorge (Azores) wind park.

A special emphasis will be made in this paper to the wind characterisation through the generation of *synthetic* time series out of the measured wind spectra, the dynamic turbine model and machine interaction and to the wind tunnel tests over a scale model of the island allowing to characterise the incoming flow.

2. INITIAL BOUNDARY CONDITIONS

The wind characteristic behaviour shows continuously variable velocities according to the atmospheric turbulence and so imposing an also variable power output, fig. 1. The fast variation on the wind velocities leads to according fast variations of the electric power its own spectra (PSD) showing energy content up to 10 Hz.

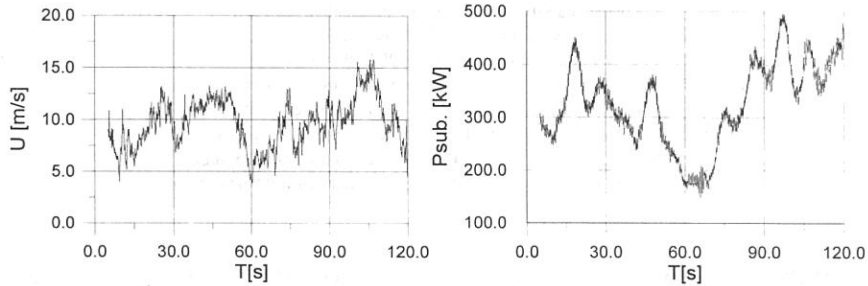


Figure 1 - Variable wind velocity and correspondent power output [2]

This form of renewable energy is also non dispatchable due to the fact that the only control imposed to a wind park lies on the maximum allowed output. This fact has greater importance with the increase of the wind turbines rated power - nowadays going towards the 1.5 MW - associated in wind parks going up to the tens of MW of installed capacity.

Two typical situations are usually the most suitable as wind park sites due to high wind velocities: *i*) isolated areas being too uncomfortable for people settlement, and *ii*) close to the sea areas, namely islands. Different grid connection problems may arise out of these situations. In the first case long transmission lines or (although it could happen simultaneously) the reinforcement of the connection substation in order to increase the short-circuit power are needed. In the case of islands - where fuel distribution costs plays a role on the feasibility - a "weak" grid, i.e. susceptible to feel power fluctuations and where the wind power output may go up to 30% of the total installed capacity (note that "weak" grids may not be an exclusive of islands). In addition is important to realise that the wind park rated power is rarely attained. The best sites in Portugal show an equivalent to 3500 hours of full charge meaning approximately 50% of the wind park rated power.

Any of these conditionings affects the economic feasibility of a wind park and so rising support for the idea that a wind park should not be treated in terms of only the global rated power. One may then conclude for the need to develop a model that allows to evaluate the reciprocal influence between the wind park and the distribution network.

In order to obtain a dynamic wind park model a few parameters must be taken into account, the assemblage being a complex process. The model has to take into consideration aspects as :

- space and time wind velocity variation and the correspondent electrical output;
- the dynamic wind turbine behaviour;

- possible wake interference, and;
- electrical oscillations between generators/transformers and capacitors.

3. THE WIND CHARACTERISTCS

The very first problem to be taken into account when a dynamic behaviour analysis is developed must be a convenient wind velocity field description for the wind turbine locations. It is clear that the simple use of an average value for the wind velocity is insufficient.

3.1 Numerical model

Out from the wind power spectrum (i. e. power spectral density - PSD) and using a modified Shinozuka method is possible to generate *synthetic* wind velocity time series and then extend it to other locations through a space correlation - the MISTRAL model - for both along and crosswind directions[3]. In a direct approach a single velocity time series for each turbine rotor was assumed as acceptable.

The generation of the *synthetic* wind time series is obtained, as a stochastic process, by an inverse fast Fourier transform (IFFT) from the micrometeorological zone of the atmospheric spectrum, where the wave length range corresponds to an approximately gaussian distribution of the velocity fluctuations. Within that range of the atmospheric spectrum the turbulence is purely mechanical, due to the fact that only "good" winds are considered, so allowing to assume both Taylor´s and Kolmogorov hypothesis.

The application of the method to the so called Davenport spectrum (k=0.008, cut-off frequency at 20 Hz) after addition of an average velocity (U_0=8 m/s, I = 21%) allows to obtain the *synthetic* time series presented on fig. 2, their only difference being the phase spectrum.

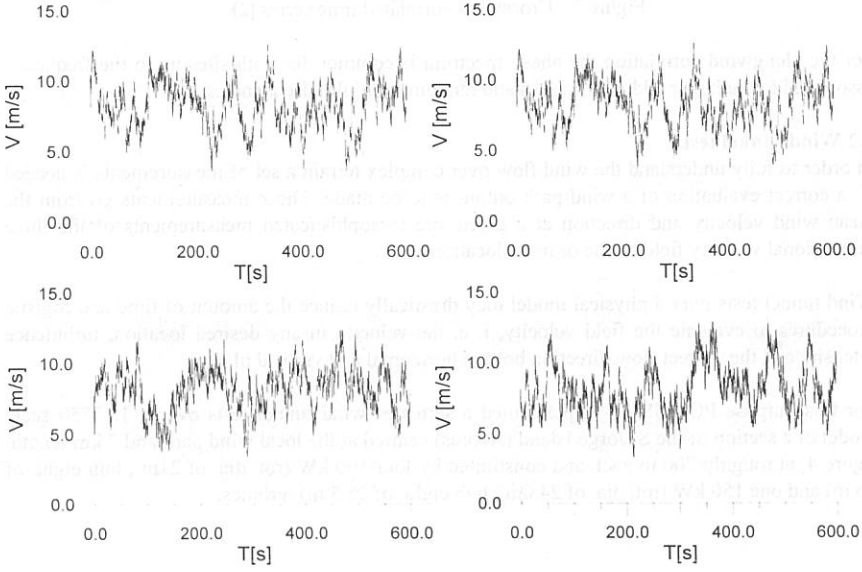


Figure 2 - *Synthetic* velocity time series [2]

The modification to the Shinozuka method consists on dropping the perturbation factor (physically meaningless) but increasing the spectrum sampling. The frequency spectrum is partitioned in two zones for the low (up to 2 Hz) and high values (2 - 20 Hz). The two *synthetic* series are then superimposed, the final one keeping the turbulence atmospheric spectrum.

When considering two different locations within the site any correlation between time series depends on the eddy dimension. If this dimension L_I is less than the distance considered (normal to the flow direction) there will be no correlation. In the other hand for bigger eddies or shorter distances the correlation is positive. Atmospheric eddies are considered on the power and phase spectrum at the frequency $f=U_0/L_I$ so the existence of correlation may be evaluated with the assumed harmonic phase in both sites. And as the spectral power must be equal, the correlation depends only on the phase spectrum. Figures 3 shows crosswind correlated time series obtained through this method.

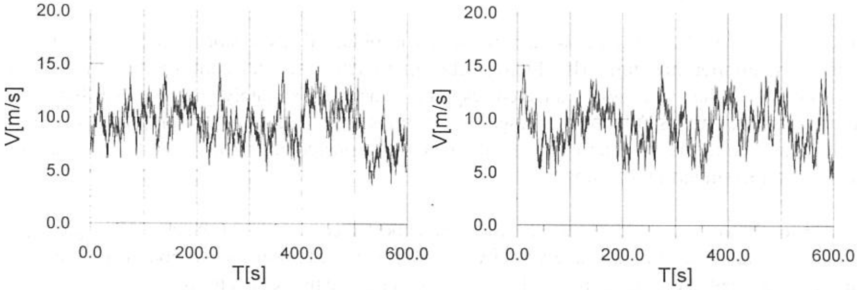


Figure 3 - Crosswind correlated time series [2]

For the alongwind correlation the phase spectrum is common for both sites up to the frequency associated to the larger eddies ($f'=x/U_0$) and random for higher frequencies.

3.2 Wind tunnel tests

In order to fully understand the wind flow over complex terrain a set of measurements is needed if a correct evaluation of a wind park output is to be made. Those measurements go from the mean wind velocity and direction at a given site to sophisticated measurements of the three dimensional velocity field at one or more locations.

Wind tunnel tests over a physical model may drastically reduce the amount of time and logistic procedures to evaluate the field velocity, i. e. the velocity in any desired location, turbulence intensity and the correct flow direction both in horizontal and vertical plan.

For this purpose PO-MISTRAL performed a series of wind tunnel tests over a 1: 3750 scale model of a section of the S. Jorge Island (Azores) centred at the local wind park and 7 km length, figure 4, at roughly 700 m a.s.l. and constituted by four 100 kW (rot. dia. of 21m , hub eight. of 26 m) and one 150 kW (rot. dia. of 24.6m , hub eight. of 25.5 m) turbines.

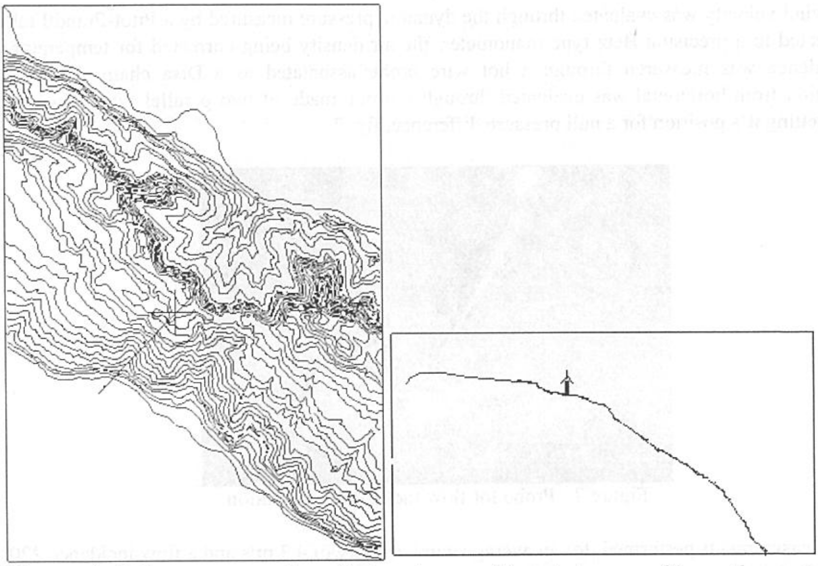
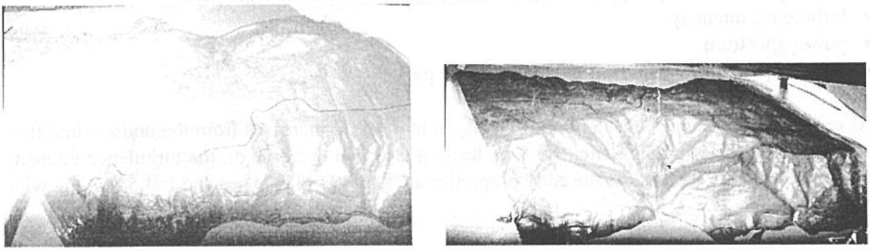


Figure 4- S. Jorge map on the wind park zone (+) and slope profile on the main flow direction



a) b)

Figure 5 - The S. Jorge Island section model. A) South side; b) North side

The test facility consisted on LNEC's open circuit wind tunnel with a suction working section dimensions of $10*3*2\ m^3$ the low turbulence flow being established through a set of six axial fans allowing 3 m/s steps for the inside velocity variation. However two of them may be continuously adjusted from 0 m/s to full speed so providing a wide set of arrangements.

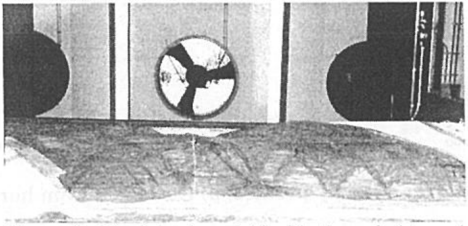


Figure 6 - The Island model inside thw wind tunnel

The wind velocity was evaluated through the dynamic pressure measured by a Pitot-Prandtl tube connected to a precision Betz type manometer, the air density being corrected for temperature. Turbulence was measured through a hot wire probe associated to a Disa chain. The flow deviation from horizontal was evaluated through a probe made of two parallel Pitot tubes and then setting it's position for a null pressure difference, fig. 7

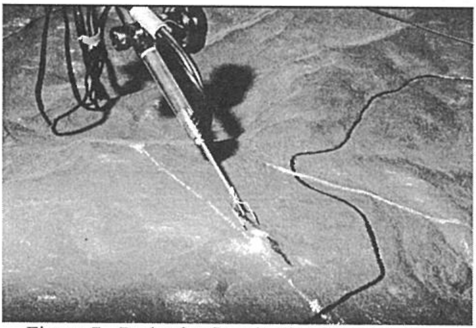
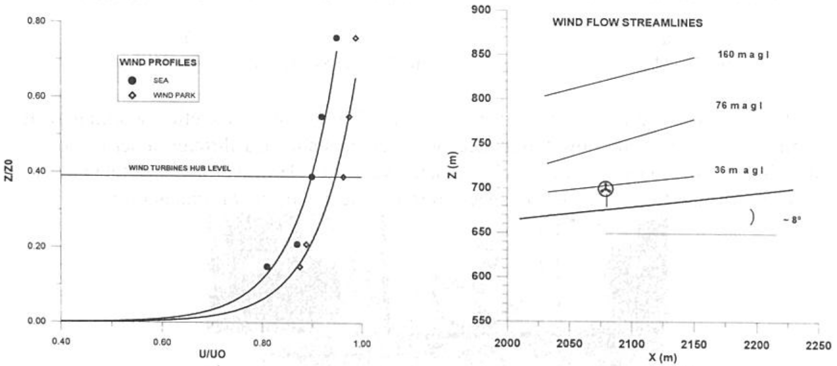


Figure 7 - Probe for flow inclination evaluation

The measurements performed, for an average wind velocity of 4.3 m/s and a flow incidence 220° from North (the most frequent one at the site), were :

- velocity profiles of the approaching flow both at the sea and the wind park
- turbulence intensity
- power spectrum
- flow direction on the vertical plan at the wind park

As expected from the terrain slope the velocity at hub height increases from the undisturbed flow at sea level to the wind park site, fig. 8 a), leading also to a decrease on the turbulence intensity due to the velocity increase as the eddy properties are kept - I=11% at sea and I=4.5% at the wind park.



a) b)

Figure 8 - a) Wind velocity profiles, b) Deviation from horizontal flow

Another important aspect to be considered on complex terrain with influence on the turbines performance evaluation is the deviation from the horizontal of the incoming flow. This aspect is usually neglected but may clearly affect the output. As shown on fig. 8 b) this deviation is, for the site of the anemometer mast at the wind park, roughly 10° upward.

Figure 9 shows the recorded velocity time series and the correspondent power spectrum that after scale correction matches the one measured on site.

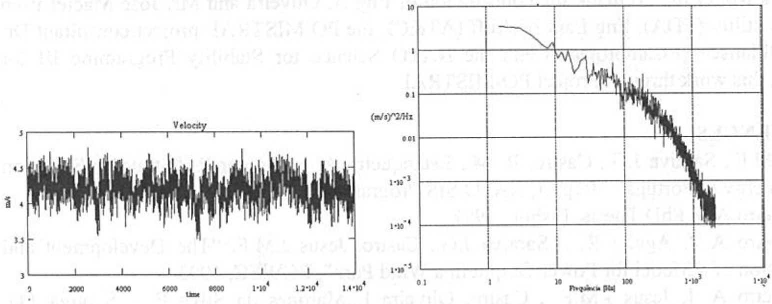


Figure 9 - Velocity time series and correspondent spectrum at the wind tunnel model

4. THE WIND PARK MODEL

The model developed - *INPARK* - enables to simulate a set of situations usual to a normal wind park, both in steady-state and transient situations being particularly suitable to assess it's integration onto a utility grid [2]. This time domain model represented by a block diagram in fig. 10 includes:

- the turbine flexible dynamic rotor model based on the well-known Glauert blade element/momentum theory and enabling both flap and lead-lag degrees of freedom for the blades at the root clamping;
- the drive train oscillation the displacement being considered concentrated on the low speed shaft;
- the tower shadow effect and it's interference on the blades aerodynamic behaviour through a procedure developed from Zdravkovich tests over staggered cylinders;
- the induction generator through a 5th order model including saturation;
- for the local grid a model of constant impedances was used the transmission lines inside the park being described by their π-equivalent representation.

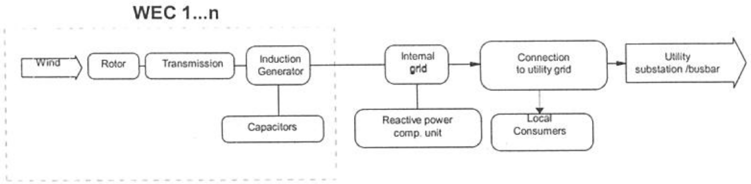


Figure 10 - *INPARK* block diagram [4]

5. CONCLUSIONS

In order to validate the assumptions here assumed concerning both to the *synthetic* wind time series generation and the wind tunnel testes a set of field measurements on the S. Jorge (Azores) wind park are currently under way. First evaluations shows promising conclusions on the followed procedure and the complete analysis will be ready within a few weeks.

6. ACKNOWLEDGMENTS

The authors would like to thank the contribution of Eng A. Oliveira and Mr. José Maciel from the Azores utility (EDA), Eng Lars Kielruff (AT&C), the PO-MISTRAL project consultant Dr. Peter Cristhiansen (Elsamprojeckt) and the NATO Science for Stability Programme III for sponsoring this work through Project PO-MISTRAL.

7. REFERENCES

1- Jesus J.M.F., Saraiva J.G., Castro, R. M., Estanqueiro A. I., Aguiar R. "Strategic Study on Wind Energy in Portugal". Report, NATO SfS Programme III, Lisbon, 1992

2- Estanqueiro A. I, PhD Thesis, Lisbon, 1997.

3- Estanqueiro A. I, Aguiar R. ., Saraiva J.G., Castro, Jesus J.M.F. "The Development and Application of a Model for Power Output in a Wind Park", ECWEC, 1993

4- Estanqueiro A. I, Jesus J.M.F. , Castro, Oliveira L.,Marques da Silva F. ., Saraiva J.G. "Development and Validation of a Wind Park Grid Integration Model"