MODELLING MACHINE INTERACTION IN A WIND PARK WITH REGARD TO STABILITY AND REGULATION: PRESENT STATUS OF NATO SfS PROJECT Po-MISTRAL

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ABSTRACT

In this paper, a general overview of NATO SfS Project Po-MISTRAL on "Modelling Machine Interaction in a Wind Park with Regard to Stability and Regulation" is presented, as well as a description of the present status of the project in terms of the main scientific achievements.

First, the current situation of wind energy in Portugal is assessed together with the economical and social importance and the expected impact of the project, in order to establish the background and justification of the project. The main objectives of the project are clearly stated, and the basic project structure is presented.

Finally, the main accomplishments achieved, as well as the main difficulties encountered, after completion of the first year of the project are addressed, allowing to draw some conclusions regarding the interaction between wind parks and the electrical distribution system.

Key-words: Wind Energy, Wind Park Models, Experimental Validation.

1. Background and Justification

1.1 Current Situation

In the beginning of the 80's the renewable energy tax incentives provided by the authorities of the State of California together with the high wind speeds registered in some locations of this State encouraged the rapid development of privately financed wind farms. In 1987 the installed capacity of Wind Energy Conversion Systems (WECS) was 1500MW provided by 15000 wind turbines.

Today the tax incentives have been removed but experience with the best wind farms has shown that wind turbines are reliable equipment (lifetimes of 20 years are currently standard figures) and can be operated with low costs. Current figures in the United States point to production costs of 0,05US$/kWh and investment costs of 1000US$/kW.

The Californian experience with wind parks has encouraged the installation of wind parks in Europe. The EUROWIN database on the 4th March 1993 reported that the installed capacity of WECS in the EC member countries is 797,21MW. If one compares this figure with the one reported for 1991 (380,2MW) it may be concluded that in two years the installed capacity has doubled. Moreover, in 1991 only 6 of the EC member countries had electric energy produced by WECS, whereas today only one country has not resorted to this form of electric energy production.

The ALTENER programme, recently adopted by the EC, aims at increasing the installed capacity and the electrical energy produced by renewable sources from 5GW and 25TWh in 1991 to 27GW and 80TWh by 2005. The impact of the ALTENER programme in the promotion of renewable energies will have an obvious impact in the increase of the current levels of wind energy penetration in the EC.

In Portugal the installed capacity of WECS is 8,43MW with the following distribution:

Continental Portugal	1,80MW
Madeira	5,58MW
Açores	1,05MW

All WECS are gathered in several wind parks, the highest nominal power of the wind turbines being 150kW. Several studies are currently underway for the installation of different wind parks both in the south coastal zone and in the mountainous regions of the north of Portugal.

The scenario sketched above for the EC member states in general and for Portugal in particular show that wind energy is penetrating steadily and that in the near future the penetration of wind energy will be reinforced. The foreseen increase in the levels of wind energy penetration will rise some technical issues which must be dealt with in order to guarantee that the quality of the utility power is not affected. Actually, wind energy being a reliable source of energy on a "year to year" basis, is an intermittent source of energy on a "day to day" basis, meaning that it is a non-dispatchable form of energy. Moreover, the power generated by the WECS generally fluctuates in amplitude over a wide frequency range which may have a non-negligible impact in the quality of the utility power, specially in cases where wind power is a significant component of the utility generation mix.

If one further takes into account that WECS are generally connected to the distribution system and not to the transmission system, one may foresee the necessity of performing an assessment of the level of wind penetration in local terms, even in cases where, globally, the wind energy penetration is modest when compared to the utility power mix.

In order to address these technical issues it is necessary to possess design tools that are able to correctly simulate the impact of the wind energy penetration in the utility distribution grids. Currently these tools do exist whenever the case of a single WECS is to be assessed. However, as far as wind parks are concerned, questions such as the level of smoothing of the power produced by the wind park and the dynamics within the park that are relevant for the operation of the distribution grid are still unanswered.

In order to provide some answers and help to solve the problems that are still pending, namely in what concerns the impact of the integration of wind parks in the utility distribution systems, a consortium involving INTERG - Instituto da Energia, INETI - Instituto Nacional de Engenharia e Tecnologia Industrial, LNEC - Laboratório Nacional de Engenharia Civil, EDA - Electricidade dos Açores and EDP - Electricidade de Portugal was formed and is being supported by these institutions and by NATO Science for Stability Programme III under Project Po-MISTRAL "Modelling Machine Interaction in a Wind Park with Regard to Stability and Regulation".

1.2 Economical and Social Importance

The introduction of large scale renewable energies in the existing utility systems shall contribute to a twofold objective: to diminish the dependency of electric energy production. from fossil fuel sources and to increase the contribution of clean energy sources to the production of electric energy.

The prosecution of these objectives becomes particularly difficult in the case of systems that are weak and/or isolated, these difficulties resulting mainly from the necessity that the electric power produced by the renewable sources does not affect the quality of the utility power.

The above mentioned difficulties are clearly more serious when considering WECS. Actually, the development of wind power at sites of high resource will be hindered by power quality considerations, even in cases where the grid is strong. Currently, there is still a lack of knowledge about the interaction between wind turbines and the grid, meaning that an identification of the technical issues associated with power quality are still on open field.

This state of affairs has contributed to the "critical view" of the utilities when considering an increase of the penetration of WECS. By proposing a project which focus on the modelling of machine interaction in a wind park and its implications with regard to stability and regulation, the consortium aims at contributing to an increase in the penetration of wind energy in the utility power mix. This aim has an impact both in economical and social terms:

- In economical terms, the full use of the endogenous energy resources, diminishes the dependency on fossil fuel sources which has a non-negligible impact in the trade balance of countries which are strongly dependent in terms of primary energy, as is the case of Portugal. The economic benefits of the full use of the endogenous energy resources is particularly important in the case of the islands where the fossil fuels energetic dependency has contributed to a delay in the economic development of these regions.
- In social terms the access to a form of energy that is clean and cheap will clearly. contribute to improvements in the quality of life the of the inhabitants.

1.3 Expected Impact

By proposing to develop models that are able to accurately simulate the behaviour of wind parks under transient situations, Po-MISTRAL Project results will contribute to a better knowledge of the impact of the penetration of wind parks in the power quality of the utilities.

It is generally accepted that the lack of knowledge, still existing, on the interaction between wind turbines and the grids has delayed the creation of suitable standards. A comprehensive understanding of the various technical problems will, certainly, facilitate the establishment of standards. Moreover, as the integration of wind parks in the existing grids is performed at a distribution level, the knowledge of the technical issues associated with power quality will further be of importance in the establishment of the local and regional energy plans.

Recently, it has been recognised that one of the factors that could limit an increased penetration of wind energy in Denmark is the lack of knowledge about the possibility of integrating steadily increasing amounts of wind power in to the electricity systems. Current figures indicate that the utilities have the flexibility to accept a contribution of about 20% from wind energy sources. This figure is generally quoted in the context of interconnected systems, the figures for isolated systems (such as the case of the islands) being generally not precise. Again, the lack of a comprehensive understanding of technical issues related to an increased integration of wind power in to the electricity systems is a limiting factor when figures such as the accepted level of contribution from wind power are quoted.

Po-MISTRAL Project aims at having an impact in:

2	Non-Linear and Linear Models for Wind Parks. Machine Interactions Inside the Park.	To develop non-linear and linear models of machine interactions in a wind park.	Interfacing existing WECS models with the new wind model in a park shall be performed within this WP. This procedure shall allow to have a detailed and general-purpose non-linear model of a wind park. In the sequence, the detailed model will be linearized in order to obtain an equivalent linear model of the park for steady-state conditions. Moreover, a transfer function of the park is to be obtained, thus allowing to work strictly on the frequency domain.
3	Dynamic Equivalents for Wind Parks.	To develop dynamic equivalents for wind parks.	The aim of WP3 is to develop dynamic equivalents for the wind park that are able to retain the relevant dynamics of the park based on the general-purpose non-linear model. The resulting reduced order model of the wind park will be obtained through the use of one of the methods currently used in power systems to determine dynamic equivalents.
4	Wind Power Effects on the a.c. System Regulation. The Special Case of Weak Systems.	To study the effects of wind power on the system regulation with particular emphasis on weak systems.	WP4 will address the special case of a weak system as an application of the models previously developed, namely by studying the impact of a large wind penetration on the regulation of an a.c. system. Within this WP, is also foreseen to perform, if possible, field measurements in order to assess the conclusions of this case study.
5	Validation of Wind Parks Models.	To validate the wind park models.	All the models developed are to be validated by specific experimentation to be carried out both in a wind tunnel and in existing wind parks. This tasks will be executed within WP5.
6	Po-MISTRAL Final Evaluation Report.	To produce a final evaluation report of the different project activities.	

4. Present Status

The status of the Project after the first year of completion is as follows:

WP0: MISTRAL General Requirements.

This preliminary workpackage is completed. The work carried out during WP0 has enabled to define the framework for the development of Po-MISTRAL Project, thus establishing the general requirements that the models to be developed have to conform to. The adequacy of the models that are intended to be used has been evaluated and the data needed to feed the models has been established.

WP1: A New Wind Model for Wind Parks.

Task 1.1 - Theoretical Wind Model.

A wind park time depending dynamic model cannot neglect the atmospheric flow local effects, specially in what concerns the different instantaneous wind speed values that affect the turbines within a park. Thus the knowledge of the simultaneous wind velocity time series at the various turbine locations is needed, including not just the average wind velocity but also the superimposed turbulence. This requirement is mainly due to the low inertia of WECS electric system and to the phenomena associated with turbulence effects on the turbine's power output, either in transient and in steady state.

A wind model for the wind parks typical spatial-scale - MISTRAL - was developed. This model is based in the "Shinozuka method", i.e. the generation of synthetic wind time series after a wind power spectral density function (PSD). For a general case, the amplitude spectrum is obtained from a parametrised wind power's spectrum density (Davenport or other) and the phase spectrum is randomly generated for a simple (or reference) series; for the correlated series, the phase spectrum is dependent on the desired cross correlations values among the series and, consequently, on their relative distance [1], [2].

The wind 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; iii) the assumption that eddies with a size below the distance H between two certain sites will be too small to affect both at the same time - and therefore will bring a null average contribution to the cross-correlation.

Within these hypotheses, 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.

The well-known Davenport spectrum shape is currently being used as the wind PSD for single, cross and along wind correlated places, with equal average speeds at the nacelle height and roughness coefficients depending on the locals. It is, however, the intention of the research team to test other spectral functions that account for the influence of the height above the ground, namely the Kaymal spectrum, and compare its performance to the Davenport PSD function.

The methodology to built the wind models was first defined and the models were developed for short wind time series (this limitation due to the size of the vectors needed for the Fast Fourier Analysis techniques). The numeric models obtained were then modified to generate longer synthetic series (to comply with the spectral gap), and the "spectrum partition" technique used for this long synthetic time series generation, was also applied to the spatial correlated wind time series model(s).

Task 1.2 - Experimental validation.

A wind park already installed in S. Jorge Island / Açores (2x100kW+2x130kW+1x150kW) was selected to monitor and validate the wind park models to be developed. Grid considerations were an important must in the selection process.

In order to start the monitoring campaign at S. Jorge Wind Park a normal cup/vane anemometer was already installed. The objective of this procedure is mainly to obtain the required information on the wind direction (not measured when the park was installed).This information will be used to allow a correct sitting of a definitive 30 meter meteorological tower currently under installation. This mast will be equipped with a 3D high frequency sonic anemometer at the nacelle height and cup/vane anemometers both at 30 meter and 10 meter high.

All wind transducers and atmospheric flow measuring equipment are previously calibrated at the wind tunnel. The experimental work will also include the construction of a physical model of the S. Jorge Island wind park area whose final dimensions are dependent on prevalent wind direction in the park. This model, that will be put forward for construction soon, will take into account the island shape and orography and will enable to characterise the wind profiles in the wind park in order to validate the dynamic models.

<u>WP2: Non-Linear and Linear Models for Wind Parks. Machine Interactions Inside the Park.</u>

The method to model the wind rotor was based in the balance of the linear and rotational momenta, by the blade non-interfering element theory. The new wind rotor model has a flexible approach based on the DUWECS models [3] and enables the blades to have both flap and lead-lag freedom concentrated on the hub. The performance of this flexible model was compared to the conventional rigid blade element model already implemented and the results point out a stronger filtering effect of the wind high frequency components, as well as a visible smoothing of the electric power output and the voltage fluctuations [4].

As far as the electrical aspects of the wind park modelling are concerned the existing detailed models of the induction generator, the reactive power compensation system and the a.c system have been conveniently adapted in order to match the specific constraints imposed by the use of the wind as the prime mover, thus preparing the conditions for the interface with both the wind and turbine models.
These procedures have enabled the development of models, denoted as detailed wind park models, that are able to simulate the transient behaviour of each WECS belonging to a park, as well as the transient behaviour of the park with respect to the utility system have been built [5], [6]. Also, an accurate modelling of all the events that may occur during the operation of the system, namely, wind park start-up, internal faults, interconnection network faults, a.c. system faults, has been performed.

In parallel, the theoretical background needed to develop a linearized model from the non-linear model has been reviewed, thus allowing the establishment of a wind park linearized model that describes small displacements about an operating point in steady-state conditions [7]. This linearized model was used to carry out a comparative study of the performance of the main reduction order techniques usually applied to obtain power systems dynamic equivalents. This preliminary study, which dealt with techniques such as balanced realisations [8], modal truncation [9], optimal Hankel-norm approximation [10], singular perturbations [11], has enabled the selection of the singular perturbations methodology as the one that is best suited for the purpose of developing a wind park dynamic equivalent able to retain the relevant dynamics.

5. Main Difficulties

One of the difficulties encountered during the Project was the selection of the wind park that will be monitored. A visit held to Açores wind parks showed that there are some problems with the operation of Graciosa wind park which could be disadvantageous for the experimentation phase. On the other hand, it was also realised that S. Jorge wind park had been in operation with no real problems. As a first conclusion it was decided that the experimentation shall be performed at S. Jorge wind park in Açores.

The choice of the data acquisition system for monitoring the S. Jorge wind park has been the next difficult point. The basic conclusion reached is that the equipment would be specified for monitoring the wind park under normal operating conditions and that in the specific tests are foreseen to be held at the wind park a data acquisition system tailored to monitor transient conditions would be used. The basic requirements for the data acquisition system is that it must be able to collect high speed data from 48 channels, simultaneously and synchronised, for a 10 minute period and then transfer the data to a computer. Currently the situation is that a market consultancy is under way in order to assess the companies that deliver data acquisition systems that could be invited to present a bid.

6. Conclusions

In this paper, a general overview of NATO SfS Po-MISTRAL Project "Modelling Machine Interaction in a Wind Park with Regard to Stability and Regulation" was presented. The most important issue addressed in the paper was, however, the publication of the main scientific results after the first year of completion of the project. These achievements are mainly concerned with:

- The development of a wind model able to describe the spatial and temporal characteristics of the atmospheric flow inside a wind park. This new wind model has the possibility of generating individual or correlated wind time series.
- The development of a wind rotor model based in the balance of the linear and rotational momenta, by the blade non-interfering element theory. This new wind rotor model has a flexible approach and enables the blades to have both flap and lead-lag freedom concentrated on the hub.
- The development of models, denoted as detailed wind park models, that are able to simulate the transient behaviour of each WECS belonging to a park, as well as the transient behaviour of the park with respect to the utility system. Also, an accurate modelling of all the events that may occur during the operation of the system, namely, wind park start-up, internal faults, interconnection network faults, a.c. system faults, has been performed.
- The development of a wind park linearized model that describes small displacements about an operating point in steady-state conditions. This linearized model was used to carry out a comparative study of the performance of the main reduction order techniques usually applied to obtain power systems dynamic equivalents. This preliminary study indicated that the technique known as singular perturbations was the best suited for the purpose of developing a wind park dynamic equivalent able to retain the relevant dynamics

Also, it should be mentioned that the experimental campaign at S. Jorge wind park has already begun and the first results are available. The models that are currently being developed are to be validated both against the results provided by these experimental field tests and by wind tunnel tests.

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References

[1] A.I. Estanqueiro, R. Aguiar, J. Gil Saraiva, Rui M.G. Castro, J.M. Ferreira de Jesus, "On the Effect of the Utility Grid Characteristics in a Wind Park Power Output Fluctuation", Proc. 1993 British Wind Energy Annual Conference BWEA15, York, Oct. 1993.

[2] R. Aguiar, A. Estanqueiro, J. Saraiva, "A Spectral Approach to the Generation of Correlated Wind Time Series" (in Port.), Proc. VI Congresso Ibérico de Energia Solar, Lisbon, Apr. 1993.

[3] Peter Bongers, Gregor Van Baars, Sjoerd Dijkstra, Okko Bosgra, "Dynamic Models for Wind Turbines", Delft University of Technology, MEMT-28, 1993.

[4] A.I. Estanqueiro, J. Gil Saraiva, Rui M.G. Castro, J.M. Ferreira de Jesus, "The Use of Stiff and Flexible Rotor Models With Regard to Wind Turbines Power Quality Assessment", Proc. 1994 British Wind Energy Annual Conference BWEA16, Stirling, Jun. 1994.

[5] A.I. Estanqueiro, R. Aguiar, J. Gil Saraiva, Rui M.G. Castro, J.M. Ferreira de Jesus, "The Development and Application of a Model for Power Output Fluctuations in a Wind Park", Proc. 1993 European Community Wind Energy Conference ECWEC'93, Lubbeck, Mar. 1993.

[6] Rui M.G. Castro, J.M. Ferreira de Jesus, A.I. Estanqueiro, R. Aguiar, J. Gil Saraiva, "The Influence of Transmission System Disturbances on the Dynamic Behaviour of a Wind Park", Proc. 1993 British Wind Energy Annual Conference BWEA15, York, Oct. 1993.

[7] Rui M.G. Castro, J.M. Ferreira de Jesus, "A Wind Park Linearized Model", Proc. 1993 British Wind Energy Annual Conference BWEA15, York, Oct. 1993.

[8] B.C. Moore, "Principal Component Analysis in Linear Systems: Controllability, Observability and Model Reduction", IEEE Transactions on Automatic Control, Vol. AC-26, Feb. 1981.

[9] J.M. Undrill, A.E. Turner, "Construction of Power System Electromechanical Equivalents by Modal Analysis", IEEE Transactions, PAS-90, 1971.

[10] Peter Bongers, "Modeling and Identification of Flexible Wind Turbines and a Factorizational Approach to Robust Control", PhD Thesis, Delft University of Technology, June 1994.

[11] P.V. Kokotovic, R.E. O'Malley, P. Sannuti, "Singular Perturbations and Order Reduction in Control Theory - An Overview", Automatica, Vol.12, 1976.