RUI M.G. CASTRO*, MSc, J.M. FERREIRA DE JESUS*, PhD
ANA I.L. ESTANQUEIRO**, MSc, R. AGUIAR**, JORGE A.G. SARAIVA**, PhD
* INTERG / IST - Instituto da Energia / Instituto Superior Técnico (Technical University of Lisbon)
** DER / INETI - Departamento de Energias Renováveis / Instituto Nacional de Engenharia e Tecnologia Industrial

The influence of transmission system disturbances on the dynamic behavior of a wind park.

SYNOPSIS: In this paper an integrated non-linear model of both the wind park and the interconnection network is presented. The model is an integration of models previously developed for each component of the system, namely wind turbines, induction generators, reactive power compensation system, transformers, feeder and possible local loads connected to the feeder. In order to draw some conclusions regarding the interaction between wind parks and the existing a.c. system, some case-studies have been performed using the developed models.

1 INTRODUCTION

In 1988 the Portuguese government issued legislation which allows independent producers to generate electrical energy and obliges the public electrical utility to purchase the energy produced by these producers.

Clearly, at that time wind power was not competitive regarding other renewable energy sources. The limited knowledge of the wind energy potentials, the little experience with the technology and, as a consequence, an incorrect evaluation of the risks by potential plant owners were the main reasons found to explain the very few projects presented in the area of wind energy.

Recently, this situation has changed. Some studies were performed in this area which allowed a better knowledge of both wind energy resources and technology and contributed to a more confident evaluation of this form of energy by private investors (1). Also, the experience with the operation of wind parks in Portugal (namely in the islands of Madeira and Açores), together with the expected reduction in WECS costs, will certainly contribute to attract more investors to the wind energy area.

In these conditions, some wind parks are currently about to be installed in Portugal and a boost is expected in the near future. Issues such as the interactions between the machines inside the wind park and the coupling to the existing a.c. system of an intermittent and non-dispatchable energy source were brought up to date, thus the necessity of possessing the appropriate tools to correctly assess both wind park steady-state and transient behavior became a must.

In order to assess the interaction between the wind farms and the utility grid to where they are connected, some computational tools have been developed with the aim of assisting both wind park and distribution system planners and designers.

These computational tools are based on models that are able to accurately simulate the behavior of wind parks under transient situations. Two types of models have been produced:

A. Models that are able to simulate the transient behavior of each WECS belonging to a park as well as the transient behavior of the park with respect to the utility system, henceforth denoted by detailed wind park models.

B. Models that are able to simulate the relevant dynamics of the park with respect to the utility system, henceforth denoted by wind park reduced order models.

These models address different problems and will be able to assist designers and planners in different but complementary issues. Whereas the detailed wind park models will assist in the design of the configuration of the wind park, the reduced order models will assist in the interconnection between the wind park and the utility grid.

This paper is concerned with the development and application of wind park detailed models above denoted as type A. models, type B. models being the subject of a companion paper "A wind park linearized model" (2).

In this paper an integrated non-linear model of both the wind park and the interconnection network is presented.

The model is an integration of models previously developed for each component of the system, namely wind turbines, squirrel cage induction generators, reactive power compensation system, transformers, feeder and possible local loads connected to the feeder.

In order to draw some conclusions regarding the interaction between wind parks and the existing a.c. system, some case-studies have been performed using the developed models. For instance, the influence that an internal power plant fault or a disturbance in the feeder has in the a.c. system, as well as the impact of utilities normal operation practices (as it is the case of a tripping in the utility grid breakers followed by automatic reclosure) in the behavior of the wind park, have been assessed.

2 DEVELOPMENT

The system studied is presented in Fig. 1

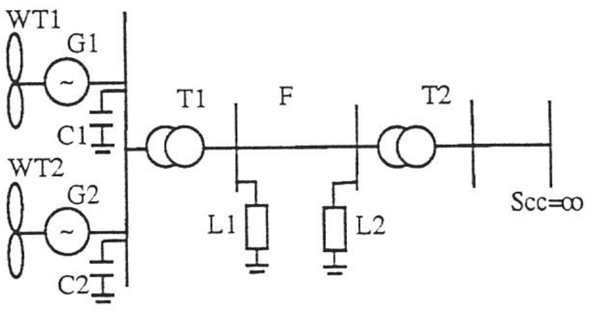

Fig. 1 - System studied.

The wind park studied was composed by two *24kVA, 400V* induction generators, squirrel cage type, each one driven by a wind turbine.

Each reactive power compensation system was sized in order that the admittance of the capacitor bank equals the slope of the linear part of the no-load magnetization characteristic of the induction generator. This size was chosen as a result of previous studies in this domain (3). Moreover, this size obeys to the Portuguese legislation.

The wind park is connected to a *30kV* feeder through a step-up transformer. This transformer feeds a local load of *5kVA*, $\cos\varphi=0.9ind$. A substation is represented by another step-up transformer, which has a *15kVA*, $\cos\varphi=0.9ind$ local load connected to the *30kV* side.

The short-circuit power at the interconnection point was assumed to be *20* times the wind park rated power, thus the a.c. system is represented by a reactance with the appropriate value.

Models have been developed to describe the behavior of the different subsystems that constitute the system studied. Also, a wind model able to generate correlated wind time series was developed, currently addressing only the wind turbine side-by-side configuration (4).

The overall model was implemented in a computer program called *INDUSAT* (5) which allows to perform several studies either in steady-state and transient conditions.

A wind turbine model was built after the blade aerodynamic characteristics and taking into account the effects of variable rotational speed, thus enabling a torque/speed characteristics to be obtained (6).

As the prediction of induction generator steady-state and transient performance requires proper account of saturation effects, a model based on *Von der Embse* circuit theory was developed (7).

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

Due to its crucial importance in the simulation of the behavior of the system, a dedicated algorithm was developed in order to obtain the steady-state operating point, i.e. the initial conditions for the set of differential equations. This technique appeals for classical power flow concepts modified in a suitable way, to calculate the relevant quantities, based only on the system parameters and on the instantaneous wind speed.

It is a current practice to describe the overall system in a reference frame rotating at the synchronous frequency *50Hz* imposed by the utility grid, due to the useful simplifications in the system's representation this approach implies. In steady-state conditions the synchronous frequency actually equals the air-gap field frequency of each one of the induction generators composing the wind park. However, in fault or isolation situations leading to both the wind park and the existing a.c. system become isolated systems, the frequency is no longer imposed by the utility grid but is actually dictated by the behavior of the turbine/generator groups.

This clearly indicates that a technique to evaluate each induction generator air-gap field frequency during transients is required, so that the relevant quantities involved can be accurately calculated. Moreover, the reference frame speed must be updated accordingly, in order to a get a systems's representation in a coherent reference frame.

In order to overcome this situation, a method for evaluating the induction generator air-gap field frequency during disturbance situations was developed. This technique is based on the fact that a change in the phase of a stator quantity means that a change in its frequency has occurred, thus enabling to evaluate the frequency through a dedicated algorithm.

As far as the reference frame speed is concerned it should reflect the changes occurred in the induction generators air-gap field frequencies. As a wind park is generally composed of a quantity of induction generators possessing equal characteristics but running in different operating points, it was thought that the reference frame speed should be set to the mean of the generators frequencies.

In order to assess the validity of the models developed some test results were obtained both in purpose-built simulators and in experimental sites. The comparison between computer and test results was found satisfactory (7),(8).

3 APPLICATIONS

The computer program *INDUSAT* was used to obtain a couple of results showing the impact of some disturbances in the feeder on the transient behavior of the wind park. For this purpose, some case-studies were selected in order to portray situations which are typical when the interaction between the park and the network is to be assessed.

Case-study I shows a situation where a fault in the feeder occurs at $t=0.5sec.$ followed by an opening of the feeder breakers at $t=0.7sec.$ and an automatic reclosure *300msec.* later. These characteristics have been chosen because they correspond to normal practices in the operation of a grid with dispersed generation. To simulate the wind input to the turbines two wind time series with a cross-correlation factor of *0.5* and an equal mean wind speed of *7m/sec.* were selected. These characteristics apply to a *25sec.* time scale, but actually we have concentrated our study in a window of *5sec.* time scale in which the two wind time series have mean wind speed of *6.74m/sec.* and *6.51m/sec.*, respectively.

Case-study II portrays a similar situation than case-study I but with the difference that the cross-correlation factor between the two input wind time series has been set to *0.7* maintaining the mean wind speed equal to *7m/sec.* However, in the selected *5sec.* time scale the two wind time series have mean wind speed of *6.96m/sec.* and *7.18m/sec.*, respectively.

Figs. 2 display the induction generators *emfs* obtained for case-study I (Fig. 2a) and case-study II (Fig. 2b) simulations. It is apparent from these Figs. that in case-study I the system will reach a stable situation, whereas in case-study II an unstable situation is obtained (demagnetization state).

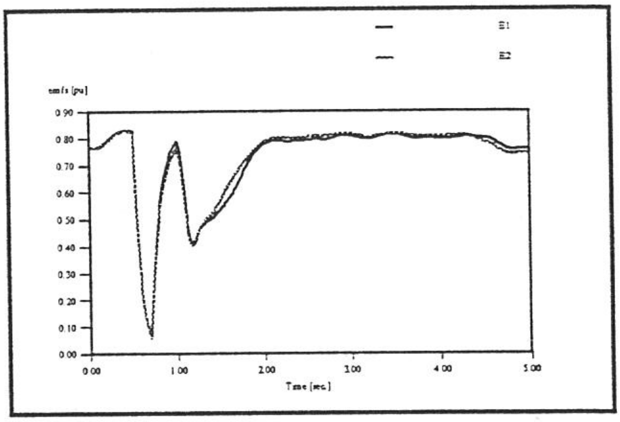

Fig. 2a - Induction generators *emfs* (case-study I).

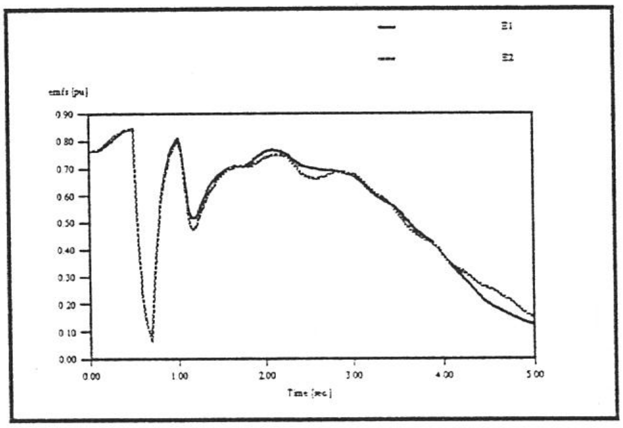

Fig. 2b - Induction generators *emfs* (case-study II).

These results indicate that, as far as the transient behavior of the wind park is concerned, both the wind's mean speed and turbulence play a very important role. Taking the case of the mean wind speed, which is easier to account for, one can remark that the mean wind speed "seen" by the park in case-study I is less than in case-study II what can partly explain the different results achieved from a stability point of view.

The role of the wind characteristics may be even more important than the fault attributes. In order to show this conclusion different fault characteristics have been simulated.

Case-study III portrays a situation in which a more serious fault has been simulated with the same wind conditions of case-study I. In the current case-study a fault in the feeder

occurs at $t=0.5sec$. followed by an opening of the feeder breakers at $t=0.8sec$. and an automatic reclosure *500msec*. later. This procedure has been accomplished in order to try to superimpose the effect of the fault characteristics on the effect of both the wind's mean speed and turbulence.

The objective of case-study IV is identical, this time by simulating a less serious fault. With the wind conditions of case-study II a fault in the feeder has been simulated at $t=0.5sec$. followed by an opening of the feeder breakers at $t=0.6sec$. and an automatic reclosure *200msec*. later.

The results obtained are presented in Figs. 3, by displaying the *emfs* of the induction generators for case-study III (Fig. 3a) and case-study IV (Fig. 3b).

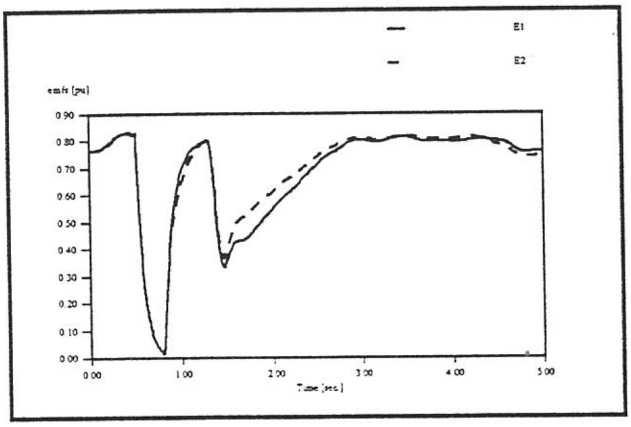

Fig. 3a - Induction generators *emfs* (case-study III).

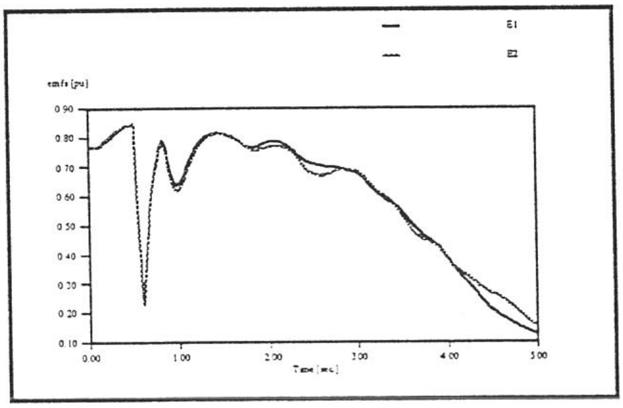

Fig. 3b - Induction generators *emfs* (case-study IV).

This results clearly show that the effect of both the wind's mean speed and turbulence may actually dictate the dynamic behavior of the wind park. In fact, in spite of these situations have been performed with the aim of reinforcing the effect of the fault characteristics, the same results concerning the stability of the system have been achieved.

4 CONCLUSIONS

A detailed non-linear wind park model has been presented, together with a model describing both the transmission system and the utility grid. The model is based on the individual models previously developed for each component of the system, namely wind turbines, induction generators, reactive power compensation system, transformers, feeder and possible local loads connected to the feeder, thus resulting in an integrated full model implemented in a computer program.

In order to draw some conclusions regarding the interaction between wind parks and the existing a.c. system, some case-studies have been performed using the developed models. The case-studies address mainly fault in the feeder simulations, in cases where the wind input time series of the turbines have different mean wind speeds but are related through cross-correlation factors.

As statistical analysis was clearly out of the scope of this paper, only some specific simulations were performed. However, the results obtained allow the conclusion that both the wind's mean speed and turbulence effects may, in some situations, be more important than the fault characteristics in what concerns the dynamic behavior of the wind park.

5 REFERENCES

(1) J.M. Ferreira de Jesus, Jorge A.G. Saraiva, Rui M.G. Castro, Ana I.L. Estanqueiro, Ricardo Aguiar, "Strategic Study of Wind Energy in Portugal", Report prepared for NATO SfS Programme III, Lisbon, Nov. 1992.

(2) Rui M.G. Castro, J.M. Ferreira de Jesus, "A Wind Park Linearized Model", BWEA15, British Wind Energy Association Annual Conference, York, Oct. 1993.

(3) 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, Aug. 1989.

(4) R. Aguiar, Ana I.L. Estanqueiro, Jorge A.G. Saraiva, "Uma Abordagen Espectral à Geração de Séries Correlacionadas de Vento", (in Port.), VI Congresso Ibérico de Energia Solar, Lisboa, Abr. 1993.

(5) Rui M.G. Castro, J.M. Ferreira de Jesus, "INDUSAT Basic Reference Guide V1.0 - Software Package for WECS Simulation", Instituto Superior Técnico, Lisbon, Jan. 1993.

(6) Ana I.L. Estanqueiro, "Horizontal Axis Wind Turbines - A Behavior's Model", (in Port.), MSc Thesis, Instituto Superior Técnico, Lisboa, Abr. 1991.

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

(8) Ana I.L. Estanqueiro, J.M. Ferreira de Jesus, D. Lalos, "Transient Behavior of a WECS Under Different Load Conditions", European Seminar on The Potential for Small & Medium Sized Wind Energy Applications, Rhodes, Jun. 1992.

(9) Ana I.L. Estanqueiro, R. Aguiar, Jorge A.G. Saraiva, Rui M.G. Castro, J.M. Ferreira de Jesus, "The Development and Application of a Model for Output Fluctuation in a Wind Park", 1993 European Community Wind Energy Conference and Exhibition, Travemunde, Germany, Mar. 1993.

(10) Ana I.L. Estanqueiro, J.M. Ferreira de Jesus, Jorge A.G. Saraiva, "WECS Unsteady Power Output Simulation", 1991 European Wind Energy Congress and Exhibition, Amsterdam, Oct. 1993.