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The use of Stiff and Flexible Rotor Models with regard to Wind Turbines Power Quality Assessment

SYNOPSIS In this paper two dynamic wind park models are compared regarding the power output quality analysis. From the electrical side both models are alike. The difference consists on the wind rotor models. One uses the rotor steady state behaviour characteristics based upon the blade element/momentum theory and takes the rotor and the blades as stiff. The second model is based on the Duwecs approach and allows the rotor two degrees of freedom: flapping and lead-lag angles. The results of both rigid or flexible wind rotor models are compared in what concerns to the relevant utility grid quantities estimated thus enabling to assess the effect of the rotor dynamics on the wind turbines/parks integration studies.

1 . INTRODUCTION

The increasing penetration of Distributed System Generation (DSG) onto the utility grids is introducing some new problems specially when the connection of these power plants into "weak" points of the grid is intended.

The integration of wind park having a rated power of the order of the tens of megawatts and delivering a continuously fluctuating non dispatchable power to the utility grid (even in its steady state working mode) can be a problem for a weak grid, specially if the interconnection transmission line is long and local consumers exist.

The lack of available 'tools' in what concerns the study of the DSG impact on the utility grid stability and performance is often overcame by simulating DGS's as constant negative loads of rated power value in the usual power flow simulation software packages.

The negative impact of this procedure on the potential investors is evident if one thinks the rated power of a wind park is not its more frequent working mode (due to various effects as wake interference, the wind turbine efficiency, etc.) and the connection and disconnection transients of the individual turbines inside a park, are not time coincident, being quite distant, and fortunately less drastic, then the "negative load" situation.

Work has been carried out for some years now to develop a 'tool' that enables both the wind park investors and the utility grid technical staff to perform the necessary preliminary studies before connecting wind parks in windy but remote areas, which, most of the times, have a weak connection to the distribution grid and are characterised by a low short circuit power value.

In a first step a dynamic model of a two wind turbine park was developed [1,2]. The model includes the utility grid near the wind power plant and enables to perform studies addressing the influence that wind power fluctuations have in the local consumers' voltage and frequency regulations.

Furthermore a simple wind model was developed to enable the generation of cross-correlated wind synthetic series, so as to include the influence of the turbulence's smoothing effect in the power output of a wind park.

In previous papers the necessary studies in order to assess the influence of the different parameters that affect the wind parks performance in terms of the electrical output were performed and the relevant parameters were identified [3].

The main disadvantage of the wind park model used then was the non-inclusion of the rotor dynamics of the turbine through its flexible behaviour. In this paper a grid connected wind turbine flexible dynamic model is presented, and the results are compared to the rigid rotor model outputs.

2. THE WIND TURBINE FLEXIBLE MODEL

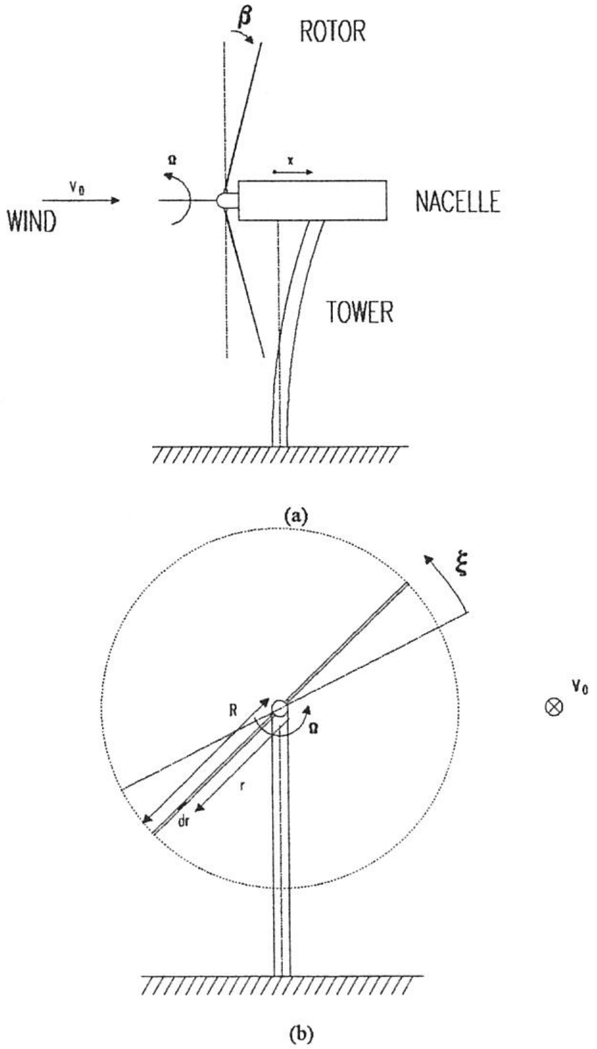
This model was developed to apply to an horizontal axis wind turbine working at what is usually called *"constant speed constant frequency"* mode.

This grid connected wind turbine flexible model consists of the integration of an induction generator and other electric energy system model developed at the INTERG/IST previously presented in the Wind Park model [1,2] and a wind rotor flexible model. The wind rotor approach is based on the dynamic model developed at the Delft University of Technology - DUWECS, to study and design flexible wind turbines [4,5,6,7].

Since DUWECS wind rotor approach is very detailed in what concerns to the structural mechanics modelling, some simplifications were performed by neglecting effects not relevant to the wind park integration in the utility grid studies.

2.1 The Flexible Wind Rotor Model

The wind rotor model degrees of freedom are the flapping and lead-lagging angles as represented in Figure 1.



(a)

(b)

Fig. 1 - Rotor flap (a) and lead-lag (b) motion

The governing equation for the flapping angle is:

$$M_{flap} - \int_0^R r^2 dm\,(\Omega + \dot{\xi})\,\beta - \int_0^R r\,dm\,\ddot{x} - k_f \beta = J_b \ddot{\beta}; \tag{1}$$

where the dots over the variables represent its time derivatives, dm is the mass of a blade element, Ω represents the shaft's rotational speed, x is the tower deflection, k_f is the rotation stiffness and J_b is the blade inertia. The flapping moment is computed based upon the lift and drag forces. For one blade element it gives:

$$dM_{flap} = r\,dL \cos\varphi + r\,dD \sin\varphi \tag{2}$$

where L and D represent respectively the lift and the drag forces and φ is the effective wind velocity angle:

$$\varphi = \alpha + \theta \tag{3}$$

being α the attack angle and θ the pitch angle.

For the lead-lag motion (ξ) the equation is:

$$M_{lag} + \int_0^R r^2 dm\, 2\Omega\,\beta\dot{\beta} - d_l \dot{\xi} - k_l \xi = J_b(\dot{\Omega} + \ddot{\xi}) \tag{4}$$

d_l being the lag damping coefficient and k_l the lag stiffness. The moment M_{lag} is computed after the lift and drag forces, and for one blade element becomes:

$$dM_{lag} = K_p\, r\,dL \sin\varphi - r\,dD \cos\varphi; \tag{5}$$

K_p is a power loss correction factor due to the tip and the root blades vortices. φ is calculated through the axial interference factor.

The available wind rotor mechanical torque $T_{Mech}(t)$ can be obtained by the equation:

$$T_{Mech}(t) = N(k_l \xi + d_l \dot{\xi}) \tag{6}$$

N representing the number of blades.

2.2 Induction Generator and Utility Grid Models

The analytical model that describes the induction generator performance is presented in [8] and [9]. Its main characteristic is to include the saturation effect of the electrical machine magnetic circuit thus enabling to simulate its non-linear behaviour. It considers that it's possible to describe the machine saturation through a unique function.

The governing equations for the induction generator in $(d,q,0)$ coordinates in a synchronous reference frame, for the stator winding are:

$$v_{ds} = -r_s i_{ds} + \omega L_{qs} i_{qs} - \omega \Psi_{qs} - L_{ds} \frac{\partial i_{ds}}{\partial t} + \frac{\partial \Psi_{ds}}{\partial t}$$

$$v_{qs} = -r_s i_{qs} - \omega L_{ds} i_{ds} + \omega \Psi_{ds} - L_{qs}\frac{\partial i_{qs}}{\partial t} + \frac{\partial \Psi_{qs}}{\partial t}$$

(7-a,b)

and for the rotor:

$$0 = -r_r' i_{dr}' - (\omega - \omega_r)\lambda_{qr}' + \frac{\partial \lambda_{dr}'}{\partial t}$$

$$0 = -r_r' i_{qr}' + (\omega - \omega_r)\lambda_{dr}' + \frac{\partial \lambda_{qr}'}{\partial t}$$

(8-a,b)

in the equations, *i* and *v* are respectively the current and voltage magnitude, *r* represents the winding resistance, *l* its induction coefficient, Ψ the magnetising flux and λ the total rotor flux. The subscripts *d* and *q* refer to the direct and perpendicular quantities and the *s* and *r* subscripts correspond to the stator and rotor variables. The line over the rotor variables signals that their values are referred to the stator. Equations (7-a,b) and (8-a,b) enable to write the state equations for the induction generator.

The equations for the capacitor bank in the same coordinates and reference frame are:

$$\frac{\partial v_{ds}}{\partial t} = \frac{1}{C}(i_{ds} - i_{dL} + \omega C v_{qs})$$

$$\frac{\partial v_{qs}}{\partial t} = \frac{1}{C}(i_{qs} - i_{qL} + \omega C v_{ds})$$

(9-a,b)

the subscript *L* refers to the transmission line current. It was assumed that for these local studies an impedance representation for the transmission line was sufficient:

$$\frac{\partial i_{dL}}{\partial t} = \frac{1}{L_L}(v_{ds} - v_{dL} - r_L i_{dL} + \omega L_L i_{qL})$$

$$\frac{\partial i_{qL}}{\partial t} = \frac{1}{L_L}(v_{qs} - v_{qL} - r_L i_{qL} - \omega L_L i_{dL})$$

(10-a,b)

being r_L e L_L respectively the transmission line's equivalent resistance and induction coefficient.

2.3 The transmission model

The transmission equation is a usual shaft's equation:

$$T_{Mech}(t) - T_{Elec}(t) - k_{tr}\dot{\alpha}_\Omega - d_{tr}\alpha_\Omega = J_r \ddot{\alpha}_\Omega \quad (11)$$

k_{tr} and d_{tr} are respectively the transmission stiffness and damping. The shaft's angle (α_Ω) is related to the rotational speed through:

$$\Omega = \frac{d\alpha_\Omega}{dt} \quad (12)$$

being J_r the rotor inertia and α_Ω the rotor angle, $T_{Elect}(t)$ is the electromagnetic resistant moment produced by the generator. $T_{Mech}(t)$ is given by equation (6).

3 . THE STIFF WIND TURBINE MODEL

A wind park time-dependent model based in a wind turbine stiff model was used and described with detail in previous publications [1,2]. Nevertheless the main characteristics of the model are presented here.

The 'stiff' wind rotor analysis in based in the well-known blade element/momentum theory analysis developed by Glauert to the fans and helicopter rotors design.

In the applications of this model the rotor is divided in elements and the rotor performance is computed by "stripes" being the performance of the whole rotor only accomplished at the end of the rotor analysis for each wind velocity value.

This is not a problem for mean wind velocity simulations but, if the purpose is to use time variable wind speed, this approach would oblige to iterate, determine the axial and tangential interference coefficients and integrate them to the whole rotor in each wind time step.

To avoid this procedure a simple method to characterise the rotors performance through a characteristic torque equation $T_M = f(\Omega, V_0)$ that accounts for the shaft's rotational speed and wind time-variation was developed.

The characteristic equation determined to model the turbine is linearly dependent on the shaft's rotational speed (Ω):

$$T_{Mech}(\Omega, V_0) = A(V_0)\Omega + B(V_0). \quad (13)$$

The wind velocity dependent parameters $A(V_0)$ and $B(V_0)$ determined for the simulated turbine, are

$$A(V_0) = A_1 V_0^\alpha + A_2 V_0^\beta + A_3$$

$$B(V_0) = B_1 V_0^\delta + B_2 V_0^\gamma + B_3;$$

(14-a,b)

the numerical coefficients and exponents are presented in reference [2].

The models for the electric equipment including the induction generator are the same presented for the flexible model, thus enabling the comparison of both wind rotor models.

The wind rotor and the generator shafts are connected through an ideal gear box. The dynamic equation that represents the shaft in this situation is:

$$J_r \frac{\partial \Omega}{\partial t} = T_{Mech}(t) - T_{Elect}(t) \qquad (15)$$

where the parameters have the same significance than for the flexible model.

4. APPLICATION OF THE WIND PARK MODELS

The wind park model is an integrated model that includes the influence of the turbulence, the dynamics of the turbine, the electric interference between the generators, capacitors and transformers inside the park, the local grid and the consumers near the park. The integrated model includes sub-models that address the different phenomena:

i) a wind model with spatial and time correlation effects;
ii) a time-domain model of the WTGS (flexible or stiff rotor) and electrical system;
iii) the characteristics of the utility grid in the interconnection busbar to the wind park

The model enables to simulate the wind turbine's performance as well as the power output of a wind park and its effect on the local loads as represented in Figure 2.

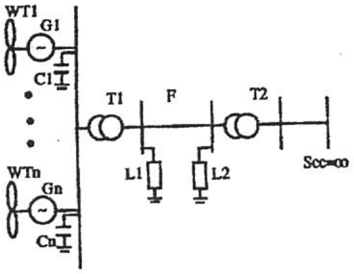


Fig. 2 - Topology of the Wind Park connection to the Utility Grid.

The needed reactive power may be delivered by the utility grid or by a local capacitor bank. This time dependent WTGS model has a wind velocity time series at the rotor height as input, the output being the mechanical torque, the shaft's rotational speed and all the relevant electrical quantities.

In this paper the influence of the rotor model type in the power output of a wind park is assessed. To achieve this purpose some other 'parallel' effects as the wind time series cross-correlation are not included (the two wind park turbines experiment the same wind time series).

The conditions at the interconnection busbar were established through the short circuit power value. This was set to 20 times the rated power of the wind park. The local loads, the transformers, the feeder and the a.c. system were modelled as constant impedances.

The wind park model was applied to the simplest configuration of both the wind park and the grid as shown in Fig. 3, where the local consumed power was set to zero, and only two turbines experimenting the same wind time series were considered.

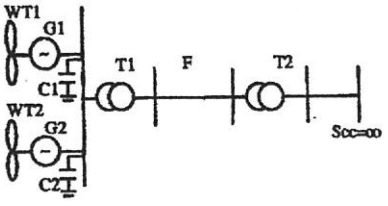


Fig. 3 - Topology of the grid to which the model was applied.

The wind turbines are 12 metres prototypes of 24 kVA rated power whose characteristics are presented in previous publications [1,2,3]. Each wind turbine is locally compensated by a 4 kVAr capacitor bank.

The grid characteristics are the same as presented in reference [3].

Some simplifications were included in the flexible model. In the simulations presented it was neglected the tower motion in the flapping and lead-lag governing equations and the shaft's damping and stiffness are not included in the transmissions equation. The gear box was take as ideal. The lift and drag coefficients were taken as linearly dependent of the blades attack angle ($C_L(\alpha)$=5.2 rad^{-1}, $C_D(\alpha)$=0.021rad^{-1}).

5 RESULTS OF THE MODELS

The output of the simulations was analysed statistically both in time and frequency domains. The time outputs presented in Figures 4 to 8 are all in per unit values with exception of the wind velocity.

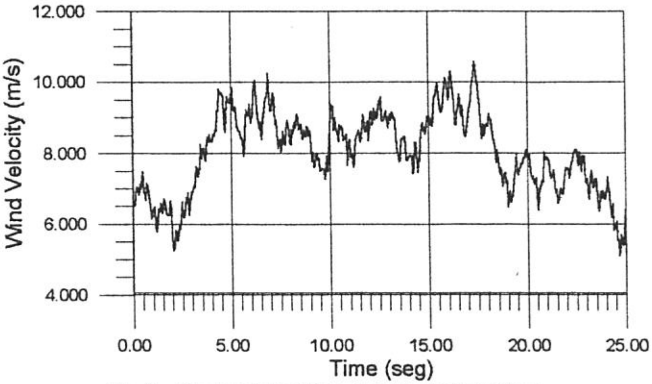


Fig. 4 - The input wind time series for both turbines (Mean wind speed =8.0 m/s)

In Figure 4 the wind time series applied to both rotor models is presented. This series used as input of the wind park model was obtained after the same 'Davenport spectrum' with 8.0 m/s mean wind speed at 10 m high.

The mechanical torque produced by each turbine and the shafts rotational speed (referred to the electrical generator side of the gear box) are presented respectively in Figures 5 and 6. In Figure 7 the difference in the wind park power output is illustrated and in Figure 8 the busbar voltage is shown.

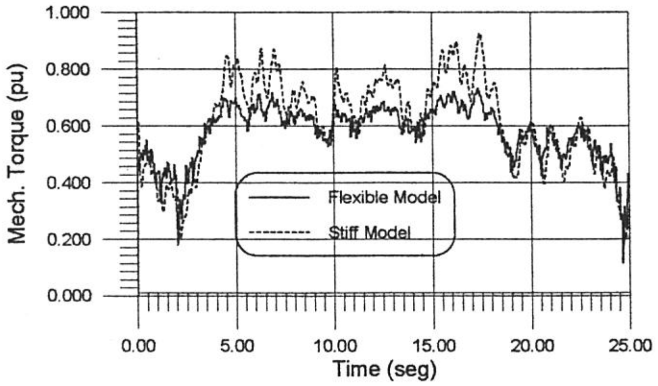


Fig.5 - Turbines mechanical torque obtained with the stiff and flexible rotor models.

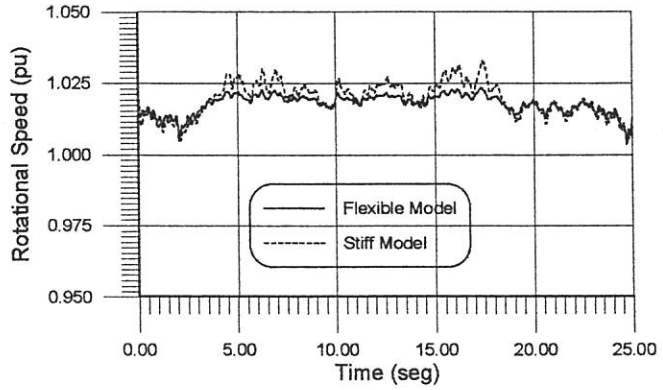


Fig.6 - Wind turbines shaft's rotational speed for the stiff and flexible rotor models (Synchronous speed=1.0).

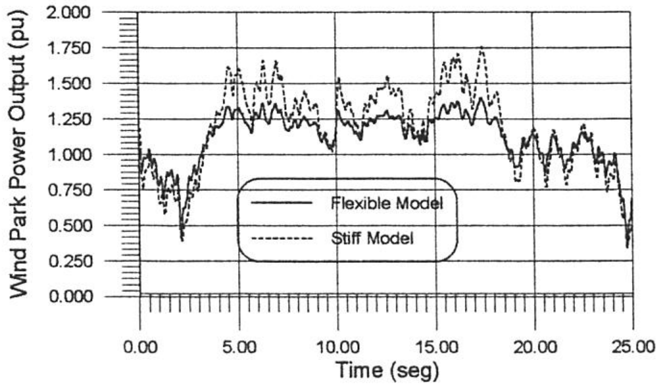


Fig.7 - Wind Park power output fluctuations for both models. (2 turbines with the same wind)

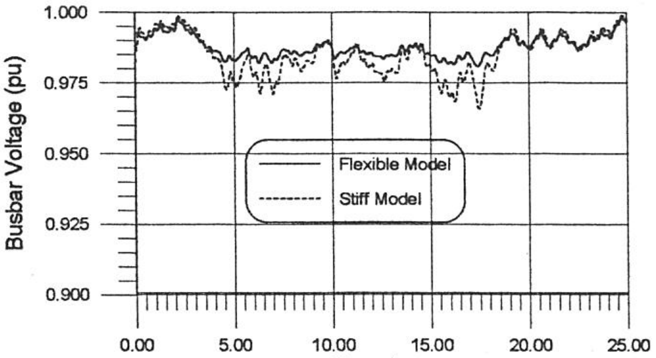


Fig.8 - Voltage fluctuation in the wind park busbar for stiff and flexible rotor models.

Figure 9 shows the comparison between the power output fluctuations' PSD for both stiff and flexible models.

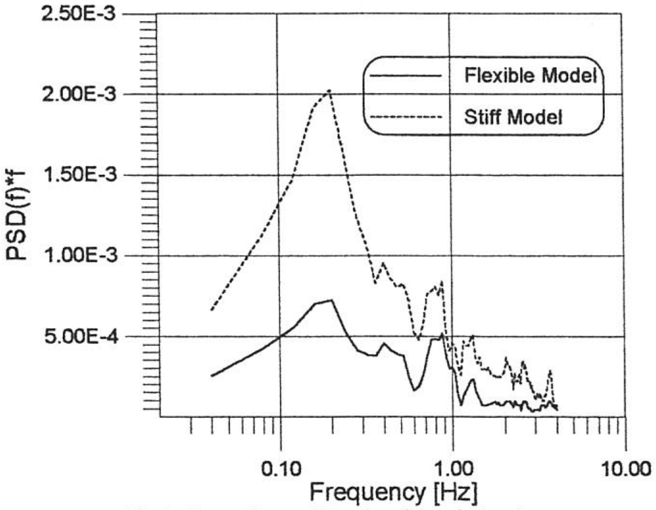


Fig. 9 - Power Spectral Density of the wind park power output fluctuations.

6 CONCLUSIONS AND ANALYSIS OF THE RESULTS

The WTGS "flexible model" is currently under development. However, and as expected from the typical wind park behaviour, it is clear from the results analysis that the non-inclusion of the rotor dynamics may introduce large deviations in a wind parks simulation performance.

In Fig. 5 that represents the shaft's mechanical torque it is possible to observe the time interval between the rigid and flexible "responses" as well as a gusts filtering effect.

Fig. 8 shows lower values in the busbar voltage deviations when the flexible rotor is considered so most of the rigid models are probably overestimating this effect.

Finally, and as expected, the Fourier analysis of the wind park power output fluctuations reveals a lower amount of energy for the flexible model output which can be attributed to a rotors filtering effect of the wind fluctuations.

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