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COMMUNICATIONS

DEVELOPMENT OF WIND FARM MODELS FOR POWER SYSTEM STUDIES

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When the wind blows, a wind farm must be able to work as an independent power station and supply current of high quality (reaction power, harmonics, frequencies, *etc*) to customers. Several research institutes and others are now doing significant work to develop wind farm models for power system studies. To indicate the main issues involved in developing wind farm models, an extract of [6] is presented in the following.

Keywords: wind turbines, induction generator, power system, dynamic simulation

1 INTRODUCTION

A fixed wind turbine model is realized as a user model in a commercial software system for simulation and analysis of power systems. Hence the model may be used together with the built-in components of the software system to constitute a detailed power system model. As presented, the model comprises a 500 kW fixed-speed, stall-controlled wind turbine, hereafter denoted as WT500. Other fixed-speed, stall-controlled wind turbines are easily implemented by changing the parameter values, while modified versions of the model may be implemented to yield other types of wind turbines. Figure 1 shows the main components of the model.

The full model may only be needed for certain studies, *eg* assessing the impact of power fluctuations from wind turbines. For other studies, parts of the model may be omitted, for example, for assessing the response to a short-circuit fault it may be fair to omit the wind speed and aerodynamic torque submodels and instead assume a constant aerodynamic torque. Windformer is a new technology protected by several patent applications. It makes possible to cave out a number of components that are normally to be found in conventional wind power systems. The result is a wind generator that does not need a gearbox or transformer (Fig. 2).

Wind speed

The user provides a time series of wind speed, $u_0(t)$, as an input to the model. This may be a measured or generated wind speed time series representing the wind speed at hub height and perpendicular to the rotor plane. The wind turbine, however, is affected by the wind speed variations over the rotor plane. These variations cause enhanced aerodynamic torque T_t fluctuations around three times the rotor frequency and harmonics thereof, whereas the other higher-frequency variations are damped. To achieve these characteristic aerodynamic torque variations, in this model, u_0 is transferred to u_t by application of filters based on [7], so that u_t approximates the weighted average wind speed over the three rotating blades. As it can be seen from Fig. 3, u_t is significantly different from u_0, so models that do not account for the wind speed variations over the rotor area will not provide the characteristic power fluctuations from wind turbines.

An alternative but more computer-demanding method could be to simulate the wind speed time series at a number of points in the rotor plane [8], a method commonly applied in computer codes for assessment of wind turbine loads.

Aerodynamic torque

The steady state relation between the wind speed and the aerodynamic power is commonly expressed as

$$P_t = 0.5 \rho A u^3 C_p \,. \tag{1}$$

As $T_t = P_t/\omega_t$, and using $u_t(t)$ instead of u, the aerodynamic torque is determined as a quasi-steady state relation

$$T_t = 0.5 \rho A u_t^3 C_p \omega_t^{-1} . \tag{2}$$

The turbine efficiency C_p is generally a function of the tip speed ratio and pitch angle. However, for a fixed-speed stall-controlled wind turbine C_p becomes a function of the wind speed only. Hence, for the wind turbine model presented in this article, C_p is simply specified as a function of the wind speed according to given data.

Mechanical drive train

The aerodynamic torque is transferred through the main shaft and gearbox to the generator shaft. By applying the detailed specifications of each element of this drive

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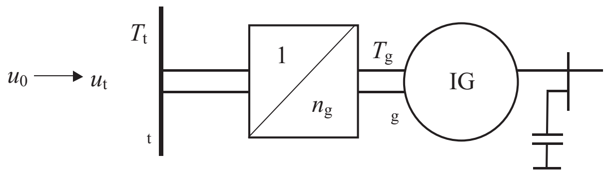

Fig. 1. Main components of a fixed-speed, stall-controlled wind turbine model.

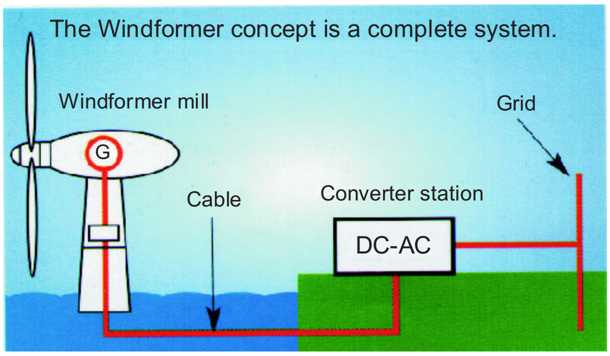

Fig. 2. A wind generator that does not need a gearbox or transformer.

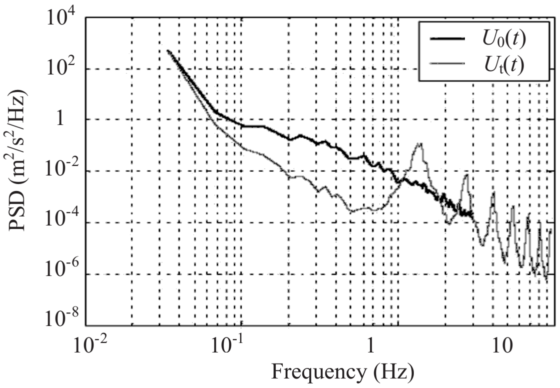

Fig. 3. Power spectrum density (PSD) of input wind speed $u_0(t)$ and weighted average wind speed $u_t(t)$.

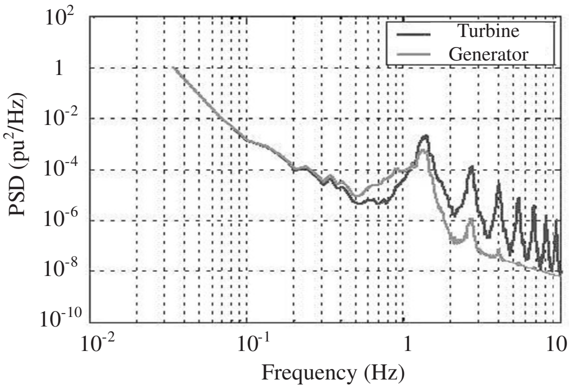

Fig. 4. PSD of simulated torque on turbine shaft and generator shaft.

train, a high-order model may be determined. A common suggestion, however, is that the dominant dynamics of the drive train may be represented by a two-mass model, *ie* the turbine and generator inertias with a shaft and an ideal gearbox between them. Hence the drive train may be approximated by equations (3) and (4),

$$\frac{\mathrm{d}\omega_t}{\mathrm{d}t} = \frac{\omega_b}{2H_t}\left[T_t - d_m(\omega_t - \omega_g) - k\Theta_t\right] \tag{3}$$

$$\frac{\mathrm{d}\omega_g}{\mathrm{d}t} = \frac{\omega_b}{2H_g}\left[d_m(\omega_t - \omega_g) + k\theta_t - T_g\right] \tag{4}$$

Applying the data for WT500, we get a swing system with a relatively large turbine inertia coupled through a soft shaft to a relatively small generator inertia. In effect, this system damps the high-frequency components of the torque fluctuations, see Fig. 4.

Induction generator

For simulation of large power systems, commonly the dynamics of transmission system elements and static loads are omitted and, to be consistent with this, the stator transients of electric machines are neglected. Hence for such simulations the induction machine is commonly modelled as a third-order model, *ie* including rotor transients (real and imaginary parts of the rotor flux time derivative) and the equation of motion ($\mathrm{d}\omega_g/\mathrm{d}t$). This approach is consistent with a phasor model simulation in the applied software tool.

For analyses of systems with few components, more detailed models may be applied, *eg* applying instantaneous values of the electrical quantities and representing all components by their appropriate differential equations. For such simulations the induction machine may be modelled as a fifth-order model, *ie* including also the stator transients (real and imaginary parts of the stator flux time derivative). This approach is consistent with a $\mathrm{d}q_0$ model simulation in the applied software tool.

In [6], various dynamic models of induction machines are compared, with the conclusion that a third-order model seems to facilitate a good compromise between simplicity and accuracy. However, stator transients of the induction generator may play an important role when performing studies of power systems including large numbers of wind turbines, *ie* indicating that a fifth-order model should be applied [10]. It appears from the investigations [6] that the two approaches lead to quite similar results and that the uncertainties of model parameters (which are always present in practical studies of large power systems) are more significant.

Capacitors

The capacitors applied to compensate for parts of the reactive consumption of the induction generator are included by using the built-in shunt impedance model of the applied software tool.

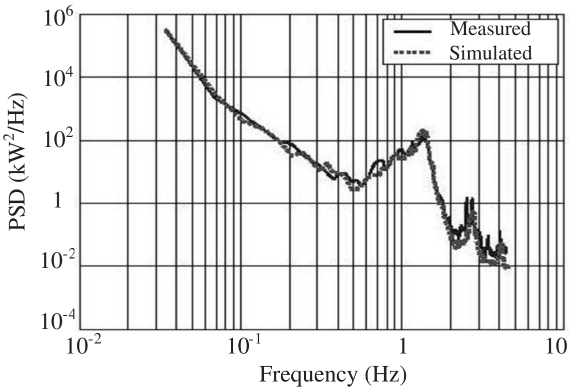

Fig. 5. PSD of measured and simulated wind turbine output power.

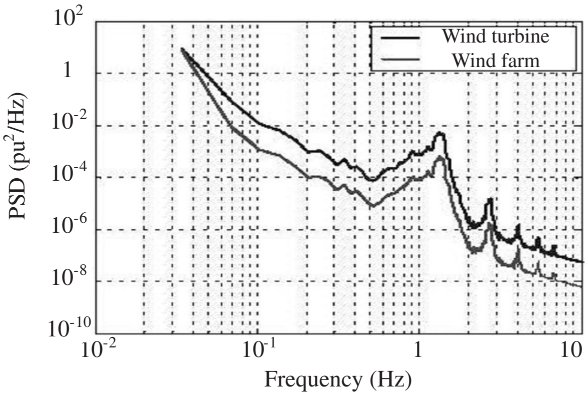

Fig. 6. PSD of simulated power from wind farm and wind turbine.

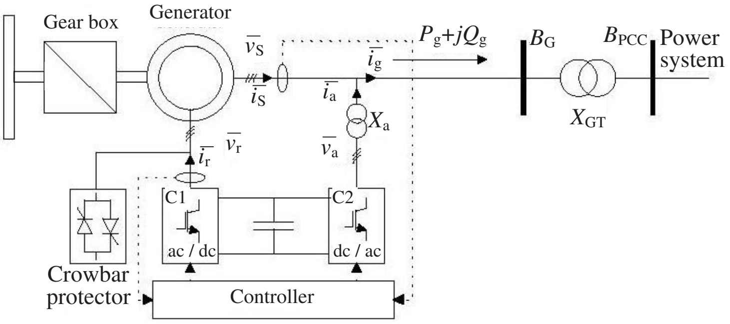

Fig. 7. Variable-speed wind turbine with doubly fed induction generator.

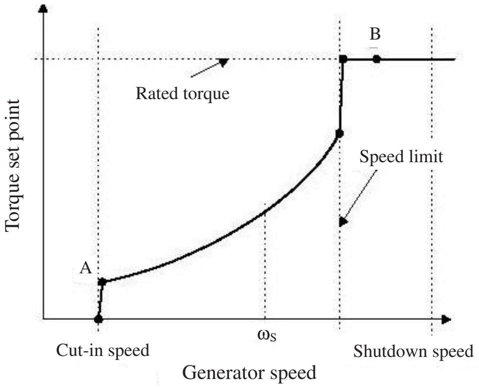

Fig. 8. Torque-speed characteristic applied for controlling DFIG wind turbines.The indicated speed limit is for continuous operation, whereas short-term speed variations may exceed this limit

Comparison with measurements

The wind turbine model has been verified by measurements on WT500. As one can see in Fig. 5, the model closely approximates the measured power fluctuations.

Aggregation

A detailed wind farm model may include detailed models of each wind turbine and their interconnection together with a wind field model describing $u_0(t)$ for each wind turbine. Applying this detailed wind farm model in conjunction with a model of the external grid, comprehensive studies may be undertaken to assess the operational implications of the wind farm. However depending on the scope of the study, alternative implementations may be designated, *eg* it may be relevant to consider aggregation techniques to let a single wind turbine model represent a large wind farm. Taking a rather crude approach, this may be done straightforwardly by keeping the pu values of the wind turbine model and including a modification of u_t to reflect that the fast power fluctuations from wind turbines in a wind farm are uncorrelated.

To illustrate the performance of the aggregation, an aggregated model of 10 WT500 wind turbines is assessed. Figure 6 shows the simulated power from the aggregated model compared with the output power from a single WT500. As it can be seen, the output power still includes the characteristic 3p fluctuations, but significantly damped compared with the output from the single WT500.

Variable-speed wind turbine with doubly fed induction generator

The basic layout of a variable speed wind turbine with a doubly fed induction generator (DFIG) is shown in Fig. 7. The DFIG is constructed from a wound rotor asynchronous machine. Variable-speed operation is obtained by injecting a variable voltage into the rotor at a slip frequency.

The cut-in and rated speed limits are mainly due to converter ratings, although the upper rotational speed may also be limited by an aerodynamic noise constraint.

In principle, the DFIG offers a number of advantages over fixed-speed wind turbines for the grid integration of wind farms. The output power tends to be smooth, as any fluctuations in aerodynamic torque result in varying rotor speed rather than changes in output power. Control of the reactive power allows the wind turbine either to operate at any chosen power factor or to control its terminal voltage, and in the event of a network fault the wind turbine could remain on the torque-speed characteristic of Fig. 8 and would not overspeed. This very benign behaviour, however, depends on the converters continuing to operate correctly during the network fault. In presently installed turbines the crowbar circuit will operate if excessive voltages appear across the slip rings. Operational experience is that even quite small asymmetric reductions in the terminal voltage, caused by remote system faults, can cause the turbines to trip. Very considerable efforts are now being made by the manufacturers to improve the "ride-through" capability of their turbines. See also *eg* [11–13] for more details on DFIGs for wind turbine applications.

2 CONCLUSION

This article gives an overview of issues related to grid integration of wind farms. To avoid unnecessary grid reinforcements or limitations of wind farms in distribution grids, this article recommends not to use rules of thumb, but rather to carry out load flow analyses, flicker assessment and so on as outlined in the second section of the article.

The application of dynamic wind farm models as parts of the power system simulation tools allows detailed studies and development of innovative grid integration techniques. Also, the importance of accurate modelling is highlighted by applying alternative simulations of a short-circuit event for illustration.

Acknowledgement

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Symbols

ρ	air density $= 1.225\,\mathrm{kg.m^{-3}}$ at $15\,^{\circ}\mathrm{C}$ and 1013.3 mbar
ω_b	base angular frequency $= 2\pi \cdot 50$ Hz electrical $(\mathrm{rad \cdot s^{-1}})$ for a 50Hz system
ω_g	generator angular speed $(\mathrm{rad \cdot s^{-1}})$
ω_t	turbine angular speed $(\mathrm{rad \cdot s^{-1}})$
Θ_t	shaft twist (rad)
A	rotor (turbine) area $(\mathrm{m^2})$
C_p	turbine efficiency
d_m	mutual damping (pu torque / pu speed)
H_g	generator inertia (s)
H_t	turbine inertia (s)
n_g	gearbox ratio
P_t	turbine power (W)
T_t	torque at turbine shaft $(\mathrm{N \cdot m})$
u	wind speed $(\mathrm{m \cdot s^{-1}})$
$u_0(t)$	undistorted wind speed at hub height of wind turbine $(\mathrm{m \cdot s^{-1}})$
$u_t(t)$	weighted average wind speed over rotor blades $(\mathrm{m \cdot s^{-1}})$

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