ENTIRE WIND-TO-POWER REPRESENTATION OF A WIND TURBINE UNIT IN ELECTRICAL POWER SYSTEM STUDIES

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INTRODUCTION

In studying the impact and interaction of wind power systems connected to an electrical network, often a detailed electrical model is used, completed with a simplified turbine representation to provide the input torque. On the other hand, in studies on the mechanical loading of the wind turbine system, the electrical power components are represented in limited manner, in fact ignoring interactions due to dynamic phenomena in the grid. To be able to perform truly dynamic studies, an entire wind-to-power representation is required for a wind turbine system. In this paper, a dynamical model of a wind turbine (WT model) extended with a fourth-order state-space model of an induction generator is compared with a measurements on a 600 kW wind turbine. In a second part of this paper, the entire wind-to-power transfer function is simplified to a first or second-order transfer function.

WIND TURBINE MODELLING

The working principle of a wind turbine encompasses two conversion processes, which are carried out by its main components: the rotor, which extracts kinetic energy from the wind and converts it into a shaft torque, and the generator, which converts this torque into electricity. Other components, such as gearboxes, controllers etc only facilitate the functioning of the principle components. To simulate the various impacts of wind power system, simulation models for each of the above simulation approaches must be developed. Therefore, the simulation model is divided in different subsystems, namely an aerodynamic, a mechanical, an electrical and a controller model. Not only a thorough understanding of the various wind turbine types and their subsystems is necessary, but also the assumptions on which these simulation approaches are based. In the next sections, the subsystems of the various wind turbines concepts will be discussed.

AERODYNAMIC MODELLING

To determine the structural response of wind turbines to dynamic excitation, a dynamical model of a wind turbine, based on a Lagrange approach of three degrees of freedom for each subcomponent (tower and three blades) has been developed, to calculate the response of the turbine to prescribed wind conditions ([1], [2] and [3]). To derive the equations of motion, the relative velocity of an arbitrary point of the turbine has to be calculated. A series of translations and rotations were calculated that relate the inertial frame attached to the tower to a rotating frame at a point of the blade. From these coordinate systems all matrices and forces may be determined in straightforward manner. The equations of motion are then expressed in terms of the generalized coordinates from the subcomponents.

The Lagrange principle is used to determine the equations of motion of the couple rotor-tower system, namely:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial h_i}\right) - \frac{\partial T}{\partial h_i} + \frac{\partial U}{\partial h_i} + \frac{\partial F}{\partial h_i} = Q_i \tag{1}$$

where T and U are respectively the kinetic and potential energy of the entire system. h_i are the generalized coordinates. F is the dissipation function. The generalized forces are Q_i. The equation provides a set of n equations where n is the number of independent generalized coordinates.

To obtain the kinetic and potential energy and the damping terms, the velocity of an arbitrary point of the blade has to be calculated. This velocity can be expressed in the local frame, after lengthy algebraic manipulations. From this equation the energy terms of the blades may be calculated. With insertion of an expression for the blade displacements in the model, the energy terms may then be expressed into the generalized coordinates. Applying the Lagrange equations finally leads to the equations of motion. The equations of motion result in a second-degree non-linear system of differential equations, in terms of generalized coordinates. The equation of motion are respectively (2):

$$\begin{aligned}&[M]\ddot{\vec{y}} + \left([C_s] + \Omega.[C_a] + \Omega[C_g]\right)\dot{\vec{y}} + \\ &\left([K_s] + \Omega^2\left([K_g] + [K_p] + [K_c] + [K_a]\right)\right)\vec{y} = \vec{Q}\end{aligned} \tag{2}$$

where [M] is the structural mass matrix, $[C_a]$, $[C_s]$ and $[C_g]$ are aerodynamic, structural and gyroscopic damping matrices, $[K_s]$, $[K_g]$, $[K_p]$, $[K_c]$ and $[K_a]$ are respectively structural, geometric, gravity, centrifugal and aerodynamic stiffness matrices. $y = \{q_i, s_{ki}, \theta_k, \beta_T\}^T$ are the generalized coordinates. The generalized forces Q originate from aerodynamic, gravity and centrifugal forces. They are obtained from the expression (3):

$$Q = \int \left(\overline{Q_a} + \overline{Q_G}\right) \frac{\delta \overline{u^*}}{\delta y} .dr \qquad (3)$$

where Q_a and Q_G are respectively aerodynamic and gravity forces, expressed in the local reference frame, u* is the local displacement vector of a point of the blade. Each of the above described matrices consists of terms associated to the tower vibrations (q), rotor vibrations (s), teetering motion (β) and rotational perturbations (θ).

The external forces on the turbine consist of the aerodynamic, gravitational, gyroscopic and centrifugal loads. Aerodynamic forces are calculated using multiple stream tube theory for arbitrary wind velocity histories. Thus not only deterministic, but also stochastic loading is taken into account. In the determination of the loads the vibrations of the system are considered as well. They result in aerodynamic damping and stiffness. The rotations of the blades introduce periodic gravitational loads and centrifugal loads as well as geometrical stiffening of the rotor blades.

The effect of the tower is to reduce the aerodynamic torque of each blade as it sweeps in front of it. In order to account for the aerodynamic torque pulsations at multiples of the rotor speed (the nP and 3nP harmonics of the 3-blade rotor), a simplified representation of the tower shadow and wind shear effects is incorporated in the WT model. This is represented by an approximate reduction ΔV_{sh} of the equivalent blade wind speed, in the $2\Theta_{sh}$ interval around the tower, as can be seen in figure 1 [4]. The wind shear effect signifies the change of the horizontal wind speed component with the altitude, within the rotor disk area [5].

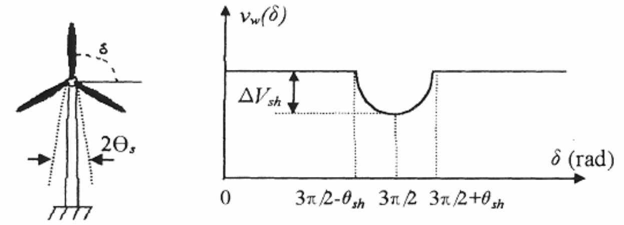

Figure 1: Tower shadow representation.

As a result, the blades experience an increased equivalent wind speed at their top position (δ=π/2, in figure 1) and a reduced one at the bottom position (δ=3π/2). The wind shear is simulated by the widely used exponential law (4):

$$\frac{Vw}{Vwh} = \left(\frac{Z}{Z_h}\right)^a \qquad (4)$$

where v_w is equivalent blade wind speed, acting on the aerodynamic centre of the blade, located at height z. v_{vh} is the wind speed at the hub height z_h and a is the shear component. The variability of the aerodynamic torque, due to periodic variations, random wind speed fluctuations and gusting, is propagated in the drive train of the WT towards the output. The magnitude of the resulting output power fluctuations, and therefore the induced voltage flicker, depends critically on the torsional characteristics of the drive train, which must be properly represented in the simulation model.

The equations of motion are derived from Lagrange equations and solved with a classical 4th order Runge-Kutta integration scheme, with automatic time step generation. These equations will be tasted into a state vector from involving a coupled system of second order differential equations with constant coefficients. Periodic time-dependent coefficients in wind turbine dynamic arise from the fact that stress producing deformations take place for both fixed and rotating components of turbines and consequently have to be described in term of fixed and rotating reference frames. This in turn leads to azimuthal dependence of the elements of matrices in the matrix – from equations of motion. These cases need a special handing using both the multi-blade coordinate and harmonic balance methods. For horizontal axis wind turbines, the situation is simpler due to the presence of constant coefficients. For aero-elastic stability calculations, the resulting natural modes and eigenvectors for tower and rotor are used to determine the coupled equations of motion of the system.

Standard “finite element” combined with a “component mode” method is adopted for obtaining the natural frequencies and mode shapes for a given turbine geometry and specified operating conditions, and the dynamic response is also defined. Thus both fundamental pieces of information, namely, the resonance and transient, are available for the turbine designer.

From the time history of the generalized coordinates, the tower and blade deflections and rotations are calculated, as well as the rotational speed variation and the teeter response. Using the standard relationships of the theory of strength of materials, the forces and moments on the subcomponents is determined as time histories. Stresses may be calculated as well.

From the time series, a more detailed analysis of the turbine dynamics is performed. It contains a BIN average of the time dependent functions for a number of azimuthal positions. Extreme loads are determined as well. The time series are further processed through a FFT analysis to obtain the spectral density functions of important quantities. The combination of the deterministic and stochastic response of the turbine allows an estimation of the fatigue life of the turbine.

MECHANICAL MODELLING

Wind turbines are composed of a rotating rotor, with two or three blades. This rotor is the aerodynamic component of the wind turbine. It captures the energy available in the wind and transfers it to a rotating shaft, located inside the wind turbine nacelle. The shaft is mechanically connected to the electromechanical converter unit. This report will not summarize all the existing electromechanical conversion in wind turbines. Recent studies have shown that the most used electrical generators in wind power plants are the doubly fed induction generator, the gearless synchronous generator and the squirrel-cage induction generator [6]. In the mechanical model, emphasis is put only on those parts of the dynamic structure of the wind turbine that contribute to the interaction with the grid. Therefore only the drive train is considered in the first place, because this part of the wind turbine has the most significant influence on the power fluctuations. The drive train converts the aerodynamic torque on the rotor into the torque on the low speed shaft, which is scaled down through the gearbox to the torque on the high-speed shaft. The drive train model is a typical 2-mass model, connected by a flexible low speed shaft, which is modelled by a stiffness k and damping coefficient c. The masses used in the model correspond to large turbine rotor inertia representing the blades and the hub, and a small inertia representing the generator.

ELECTRICAL MODELLING

There are different strategies for modelling the generator and, if present, the power electronic converter for the various simulation approaches [7]. The main reasons are the different approaches towards the modelling of the network. With the sub-transient simulation approach, it is modelled with differential equations, calculating the instantaneous values of voltages and currents. With the transient approach, it is modelled with algebraic load flow equations, calculating the RMS-values of voltages and currents as a function of time. With the power balance approach, it is either neglected or only network congestions are taken into account. The modelling of the generators and, if present, the power electronic converters must be consistent with the network modelling, because the generators and converters directly interact with the network.

While deriving the models, special attention has been paid to increasing the computational speed of the simulation program. An important increase in speed is realized by the use of the dq0 transformation (Park transformation) not only for the generator, but also for all other electrical components. The Park transformation is common use in electrical machine models. The simulation program provides the fourth-order state-space models of squirrel cage and doubly-fed induction machine, the sixth-order state-space model of the synchronous machine (with inclusion of the damper cage on the rotor) and second order state space of the permanent magnet synchronous machines for speed, active and reactive power.

CONTROLLER MODELLING

Modern wind turbines are controlled both in active and reactive power. The reactive power control can be performed by controlling the reactive current of the generator itself, if the generator is grid-connected through a power electronic converter. Otherwise, a STATCOM or SVC (Static Var Compensator) is used in parallel with the generator. Both options allow control of reactive power, independently of the active power control. Reactive power control is not further discussed here.

The active power control is done by pitch control, and, if the generator is grid-connected through a power electronic converter, by control of the speed and generator active current. Generic algorithms for pitch and speed control is found in literature, however the control details are often the intellectual property of the turbine manufacturers. An example of an entire control system of a variable-speed turbine can be found in e.g. [8] and [9].

VERIFICATION OF ELECTRICAL MODELS

Due to the modularization each sub-model could easily be tested independently of the others and when accepted, the complete simulation model was formed. This model is tested with a 600 kW dual speed, controllable pitch, asynchronous generator wind turbine T600-48 of Turbowinds, installed in the wind farm of Zeebrugge.

Several modes of operation can be identified: start-up mode, power production mode, shutdown mode and emergency modes. In the start-up mode the turbine is accelerated and the generator is connected to the utility grid. In the power production mode power is extracted from the wind and transferred to the utility grid. In the shutdown mode the generator is disconnected and the turbine is decelerated. The system is in an emergency mode if malfunctioning is been detected. In an emergency mode backup systems are invoked to provide a safe shutdown. Starting up and shutting down the wind turbine causes large, sudden changes in active and reactive power in the system. Also, both the active and reactive power of the wind turbine can fluctuate widely in turbulent wind conditions. These rapid power fluctuations can, in turn, cause voltage variations that are detrimental to voltage sensitive loads and/or result in objectionable disturbances to electric lighting levels (flicker).

Simulations were run to check the system's response to acceleration of the wind speed (case 1: Medium wind) and at full output power (case 2: High wind). In both case the wind turbine has a rotation speed of 23 rpm and is grid connected.

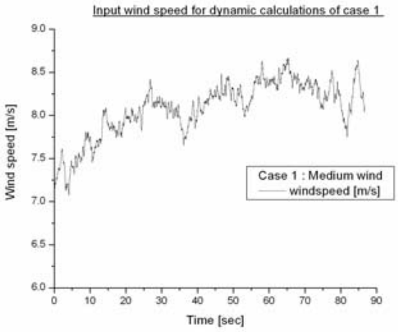

Figure 2: Input wind speed for dynamic calculation of case 1

Figure 2 shows the input wind speed for dynamical calculations of case 1. Figure 3 compares the active power of the measurements with the dynamic calculations for case 1 and figure 4 compares it for case 2. The mean wind speed for case 2 is 15.3 m/s with a turbulence intensity of 13.4 %.

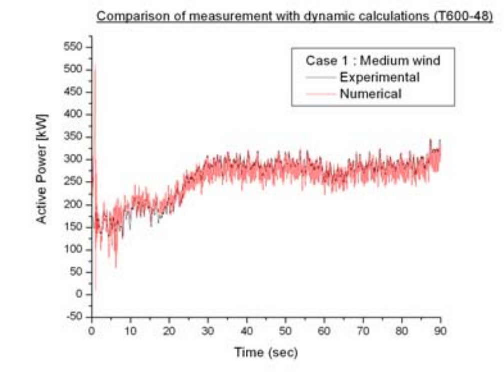

Figure 3: Comparison of measurement with dynamic calculations for case 1 (wind turbine = T600-48)

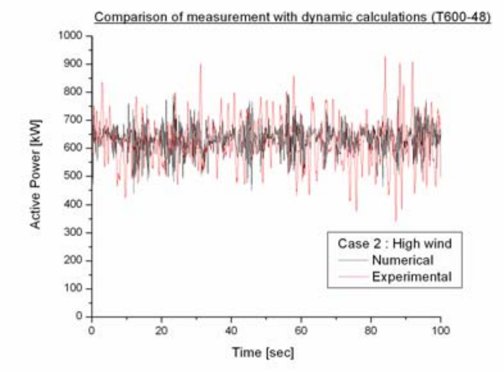

Figure 4: Comparison of measurement with dynamic calculations for case 2 (wind turbine = T600-48)

The active power calculated with the dynamical model represents the measurement data of a 600 kW wind turbine with induction generator very well. Experimental data of other wind turbines with other generators (doubly fed induction, synchronous and permanent magnet synchronous machines) are missing to validate the simulation model with this real state.

MODEL REDUCTION

An attempt to reduce the model complexity as described above is performed, with the purpose of generating a numerically simple model to perform power system simulations for a rough estimation of the impact of wind power on transient power and voltage fluctuations.

With the model from [9], the frequency characteristic of the entire wind-to-power transfer function has been investigated. For this, sinusoidal wind speeds were imposed on the model, which resulted in sinusoidal output powers of the same frequency. This suggests that the entire system is approximately linear. The amplitude of the sinusoidal output power depends on the frequency of the wind speed fluctuations. Figure 5 shows examples of simulation results with wind speed signals with an average value of half the rated wind speed (upper part) and 1.2 times the rated wind speed (lower part), for frequencies equal to 0.05, 0.5 and 2 Hz. The corresponding output power is shown in Figure 5.

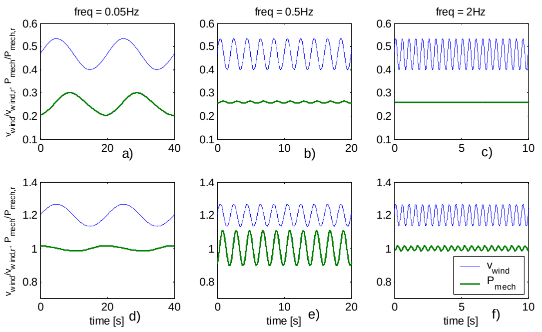

Figure 5. Wind speed and mechanical power for two values of average wind speed and three different wind speed fluctuation frequencies

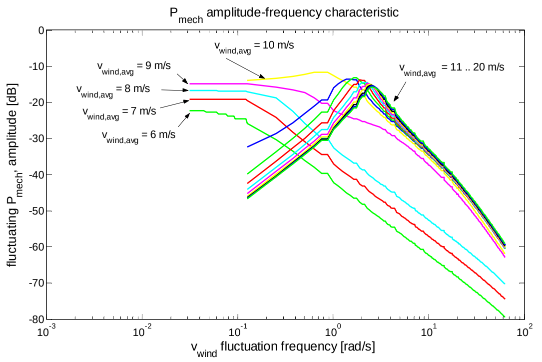

Figure 6: Frequency characteristic of power fluctuation amplitude

All simulation results, for a large range of frequencies and average wind speeds, are summarized in figure 6. The 10-logarithm of the amplitude of the turbine power oscillations is plotted against the frequency of the wind speed oscillations. This plot can be interpreted as a Bode diagram, and it allows estimating equivalent transfer functions for the variable speed pitch-controlled turbine system.

Two sets of curves can be distinguished in figure 6: curves for low average wind speed (below rated wind speed), behaving as a low-pass filter, and curves for higher average wind speed (above rated), behaving as a second-order transfer function. The explanation for this phenomenon and further results are described extensively in [10] and [11]. The results from figure 6 are used to identify the structure and parameters of the equivalent wind-to-power transfer function, which is either a first-order transfer function or second-order transfer function, with a gradual transition between both for wind speeds around the turbine's rated wind speed (extensively explained in [10] and [11]). This equivalent transfer function is numerically very simple and can further be extended with control loops for other operation modes, for instance operation at reduced power in order to be able to deliver balancing power if required [10][11].

The equivalent transfer function is derived from the frequency characteristic of the detailed model, and thus contains the most relevant time constants for the wind-to-power transfer function. However, some information about the turbine operation is lost if the equivalent transfer function is used, such as turbine speed and mechanical loadings. The transfer function is therefore only adequate for a first estimate of the amount of wind energy that a grid can adsorb, given some criteria concerning accepted power quality distortions and power transients. A comparison between the calculated output power from the detailed model and the equivalent transfer function is shown in figure 7. This figure shows the wind speed, used as input for both models (above) and the resulting calculated output powers. The correspondence between the detailed model and the equivalent transfer function is satisfying.

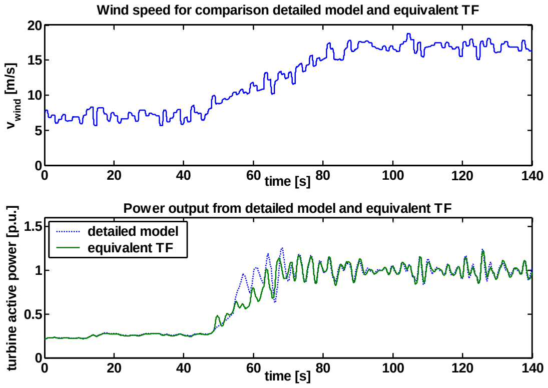

Figure 7. Wind speed signal (above) and corresponding power output (below) from the detailed model and the equivalent transfer function

CONCLUSION

The authors have performed detailed modelling tasks of aerodynamical, mechanical, electrical and control aspects of wind turbines, the latter taken from literature. All model components are integrated in a entire wind-to-power transfer function, which is in a second step considerably simplified to a first or second order transfer function. This model simplification may only be executed if the purpose of the model allows it, for example to estimate roughly the transient power fluctuations in a grid, given a continuous wind speed signal.

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