The Impact of the Modelling Depth of Mechanical and Electrical Sub-Models on the Simulated Electrical Properties of Wind Turbines

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1 Abstract

As the share of wind energy increases, it is critical that the requirements defined by the grid operator are fulfilled before connection to the grid is established. Nowadays, the measurements required for the certification of a wind turbine's electrical properties are run in the field. This is time consuming and costly, due to limited accessibility and the fact that natural factors, such as wind speed, cannot be defined freely and consequently tests are not reproducible.

The certification procedure includes mechanical, structural and electrical requirements for the behaviour of the wind turbine in case of normal and fault operation. The required tests for such a certification are described in the FGW Technical Guideline 3 (TR3 - Determination of the electrical characteristics of generating units and installations at medium, high and extra high voltage grids [FGW16]).

For the simulation approach of such an electrical certification on a system test bench no qualified statements concerning the necessary modelling fidelities for the different test cases are known. Therefore, in this paper models with different modelling depth and their impact on the simulation results are analysed with respect to the representation of the wind turbine's electrical properties. Consequently giving a recommendation on future modelling.

A holistic wind turbine model is built up, consisting of aeroelastic, mechanic and electric models. The mechanical elements, from the rotor blades to the generator, are modelled with SIMPACK by means of multibody simulation (mbs). The mbs model is connected with the aerodynamic and electrical sub-models in SIMULINK. The aim of this paper is to analyse the impact of the differently detailed models of the mechanical system on the properties relevant for the electrical properties of the wind turbine.

To define the sub-model's level of detail they are successively refined with a variety of fidelity levels. The rotor blades are represented by rigid blades and can be refined up to elastic blades using modal based reduction with different number of eigenmodes. In the second step, the drivetrain model is refined from a single mass to a three-mass-oscillator. The different levels of detail are compared with respect to their impact on the electrical properties.

2 Introduction

In recent years, system test benches for multi-megawatt wind turbines have been developed nationally and internationally. These test benches make it possible to test complete drive trains of wind turbines in the laboratory under reproducible conditions. An example for such a test bench is the hardware-in-the-loop (HiL) system test bench of the Center for Wind Power Drives (CWD) at RWTH Aachen [AVE17].

Among others, such system test benches can be utilized in the future to determine the electrical properties of a wind turbine, which are necessary for their certification. Due to missing components on the test bench (e.g. rotor blades), the question is, how detailed these components are required to be emulated. Thus, the main purpose of this paper is to investigate, which impact these missing mechanical parts have on the electrical components and hence the derived electrical properties. This is analysed with the help of a holistic wind turbine simulation model that comprises mechanical sub-models of different levels of detail. From this simulations, the requirements on the mechanical interface and on the software, i.e. the hardware-in-the-loop simulation and corresponding control system, can be derived.

3 Modelling

The overall wind turbine model (see Figure 1) consists of six partial models. The aeroelastic model (RAISE) calculates the input loads applied by the wind for the mechanical drivetrain model (SIMPACK, MATLAB/SIMULINK). At the same time, the mechanical powertrain model is coupled with the electrical generator model (MATLAB/SIMULINK), which provides the load torque of the generator as a function of the input torque. Furthermore, the converter model (MATLAB/SIMULINK) and the grid model (MATLAB/SIMULINK) are located on the electrical side of the modelling. The wind turbine controler (MATLAB/SIMULINK) is superordinate to the sub models.

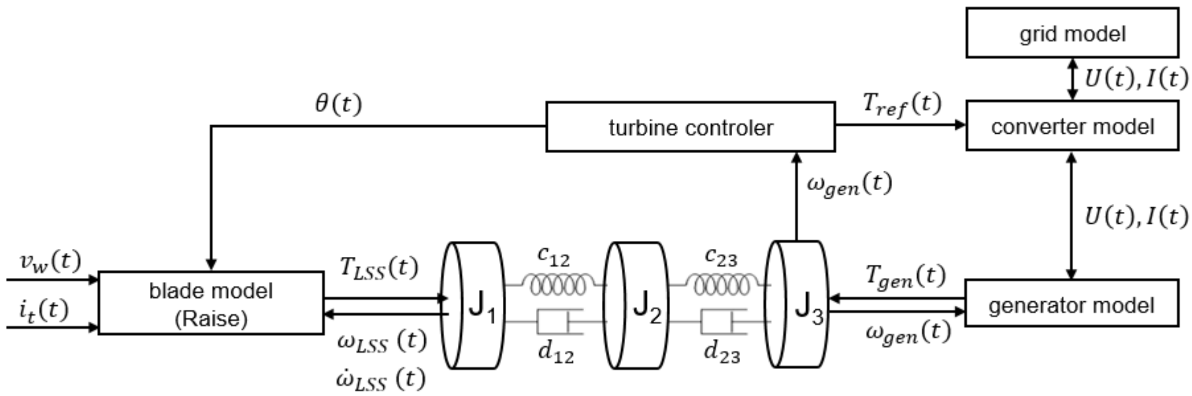

Figure 1: Overall wind turbine model

One of the missing parts on the test bench are the rotor blades. Therefore the question is, how and with which detail level the rotor blades need to be emulated on the test rig, to get the same behavior like on the field. Figure 3 compares the torsional moment of inertia of the test bench [AVE17] and the real turbine model [MAT18]. The green area represents the torsional moment of inertia for each body. All the inertias (area of the green circle) are equalized to the low speed shaft. It can be seen, that there is a huge difference between the very large rotor inertia of the real wind turbine and the small inertia of the test rig.

Therefore in this paper the model depth of the blade model and the drivetrain will varied and the impact on the generator rotational speed, as well as on the electrical power will be evaluated. The blade model varies from a rigid blade up to an elastic blade with eigenfrequencies up to 20 Hz. The drivetrain model varies from a single mass up to a three mass-oscillator. All the electrical models are not changed in the detail level.

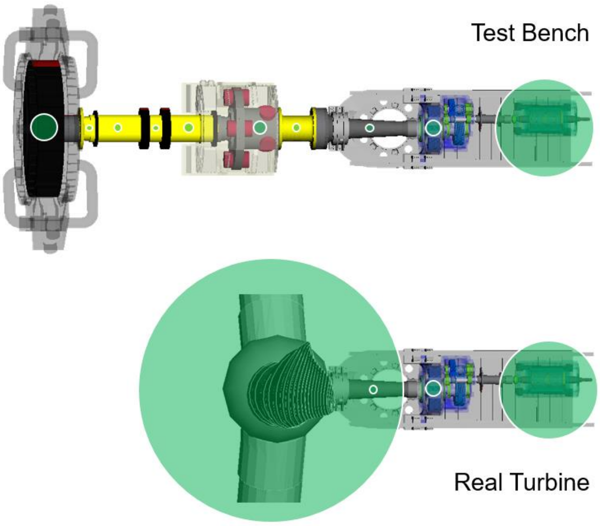

Figure 2: Physical characteristics of test bench and real wind turbine

First of all a detailed model was set up in SIMPACK to calculate the modal behavior of the wind turbine. Initially, the calculation was carried out at nominal operation state with rated speed and 0-deg pitch angle. Two coupled rotor and drivetrain eigenfrequencies were identified [MAT18].

The first natural frequency of the drivetrain and the first natural frequency of the blades in edgewise direction formed the lowest torsional eigenfrequency of the wind turbine. Due to the excitation mechanism in wind turbines, e.g. wind shear and tower shadow at low frequencies the torsional modes needs to be considered. To represent the described mode shapes (1^{st} and 4^{th} mode shape shown in Figure 3) a simplified three-mass-oscillator is modeled and validated against the detailed simulation model of the wind turbine [MAT17]. This simplification of the drivetrain and blades model needs to be done due to the real time requirements for the HiL-test on the test bench.

In Figure 3 it can be seen, that the mode shape 1 and 4 initiate a resulting torque into the drivetrain and thus will be visible in the drivetrain torque. In the case of mode shape 2 the forces introduced into the hub add up to zero. The mode shape 3 results in a force, which loads the tower.

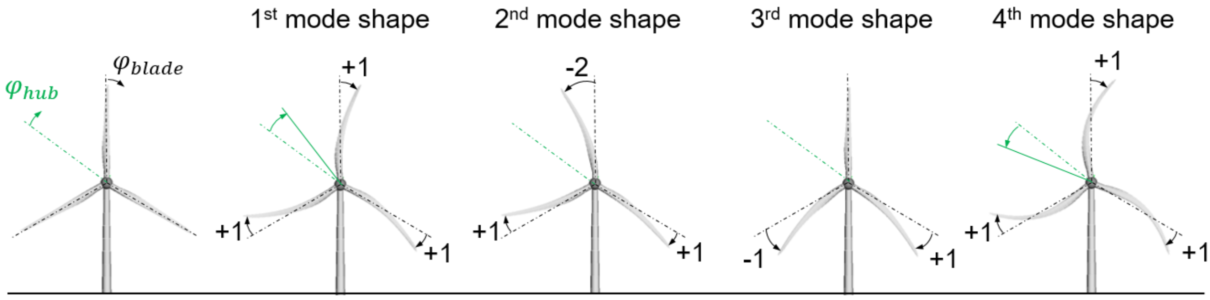

Figure 3: Characteristic mode shapes of the rotor blades

As already mentioned, the simplified three-mass-oscillator will be used in a later stage for the HiL test with representation of the first two torsional eigenfrequencies of the wind turbine on the test bench. HiL methods enable a realistic mapping of the actual dynamic behavior of a wind turbine on the test bench. The aerodynamic loads are applied with the program RAISE which is developed by the Aerodynamic Institute of Aachen (AIA). It considers the turbulence, tower shadow, pitch angle and the vertical wind shear. The pitch angle and the generator torque is controlled by the turbine controller. In total six different model depth has been compared, see Table 1.

	wind shear	tower shadow	elastic blades	one mass	two mass oscillator	three mass oscillator
M0	x			x		
M1	x	x		x		
M2	x	x			x	
M3	x	x	x (2 Hz)		x	
M4	x	x	x (10 Hz)			x
M5	x	x	x (20 Hz)			x

Table 1: Overview of model depth

4 Results

Figure 4 shows the wind speed, the rotational speed of the generator and the fast-fourier transformation (FFT) of the generator speed for different model depth. The wind speed is 16 m/s and has a turbulence of 12 %. The rotational speed of the generator is fluctuating around 1100 rpm. The gearbox ratio is ~63 and thus the input rotational speed 17.5 rpm. The frequency spectrum of the generator rotational speed for each model depth shows its first peak at ~0.88 Hz, which is the result of the 3P excitation from the tower shadow and vertical wind shear. Additionally the 6P excitation is visible at ~1.76 Hz. The first torsional eigenfrequency is around 2.5 Hz, which is excited by the 9P excitation. This peak can only be seen in M3, M4 and M5. The model depth M4 and M5 have also a slight peak at 4.5 Hz, which is the second torsional eigenfrequency. The frequency spectra of the rotational generator speed for the model M4 and M5 are almost identical. At model M2 (two-mass rotary oscillator with rigid rotor blades), the first torsional eigenfrequency shifts to about 2.9 Hz. This is due to the stiffening of the rotor blades, which makes the overall system appear stiffer by the degree of rotational freedom. Since the model depths M0 and M1 contain no flexibility, but only a total inertia, the torsional eigenfrequencies are not found in the FFT. For the correct mapping of the dynamic behavior of the drivetrain, at least the model depth M4 is recommended.

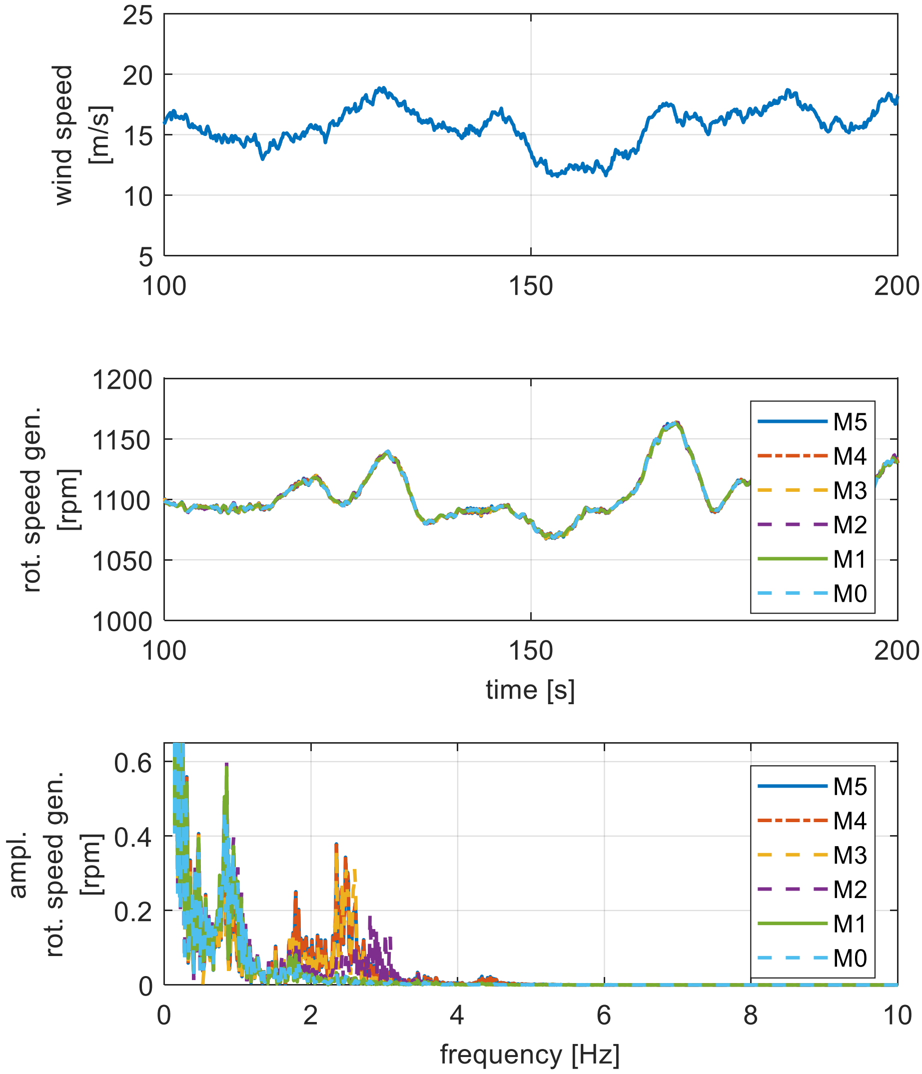

Figure 4: Comparison of the generator rotational speed for model depth M0-M5 with 16 m/s wind speed and 12% turbulence intensity

For further analysis, the model depth M4 is considered, in order to check the direct influence of the rotor on the electrical model. Thus the electrical and mechanical power are compared.

Figure 5 illustrates the electrical and mechanical power for a wind field with 16 m/s wind speed and 12% turbulence. The temporal course of the electrical power fed into the grid follows the mechanical power at the generator up to a deviation of about 2%. The deviation is due to losses in the generator and converter taken into account in the simulation. The mechanically excited natural frequencies of the drivetrain are equally reflected in the FFT of the electrical power fed into the grid. The 50 Hz oscillation superimposed in the active power results from a dc component of the grid current in the range of several 10 Amperes. This dc component is caused by the grid current controller which is not inside the scope of this paper. The 50 Hz oscillation is only visible at the grid side and is, thus, not associated with the mechanical drivetrain. The 9P excites the first torsional eigenfrequency of 2.5 Hz. For the sensitivity analysis, the mechanical power at the generator can therefore be considered instead of the active power fed into the grid.

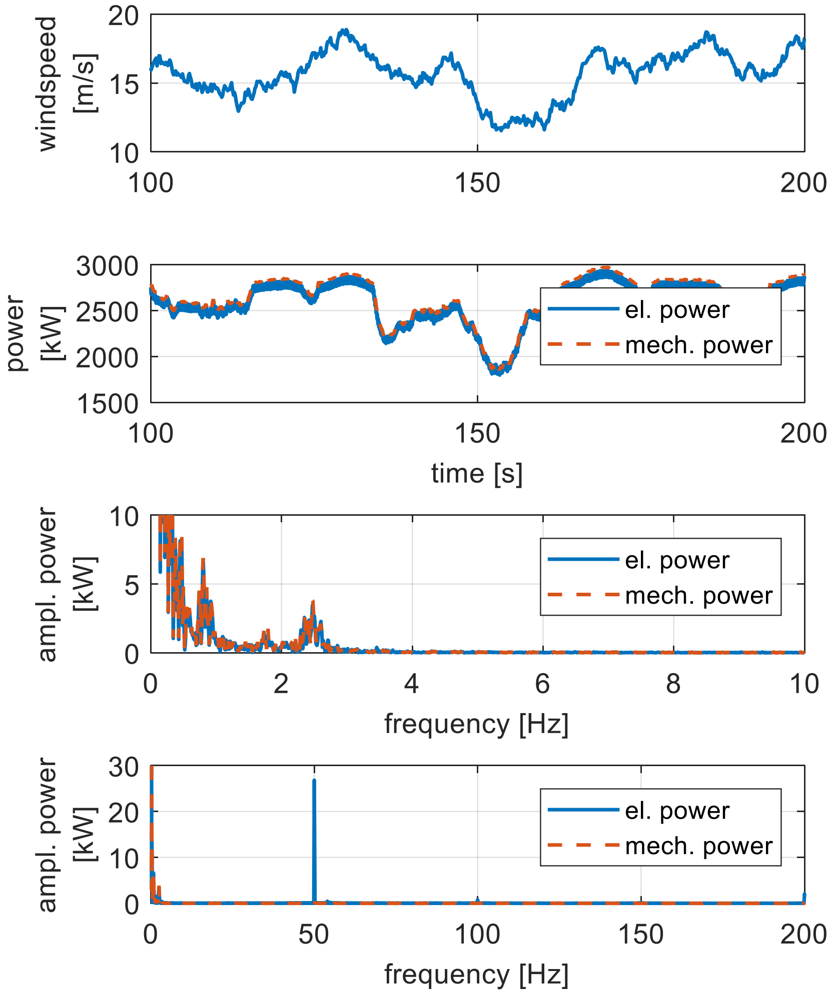

Figure 5: Electrical vs mechanical power for model depth M4 with 16 m/s wind speed and 12% turbulence intensity

Conversely, the mechanically excited natural frequencies of the drivetrain do not affect the dc-link voltage. The frequencies are visible in the spectrum of the simulated dc-link voltage, but with a negligible amplitude (see Figure 6). Only the already mentioned 50 Hz oscillation is clearly visible there (Figure 6). The dc-link voltage can therefore be assumed to be constant in the frequency range relevant for the mechanical drivetrain, so that the mechanical and electrical models are decoupled for sensitivity analysis. Far-reaching simplifications are therefore possible for the inverter model.

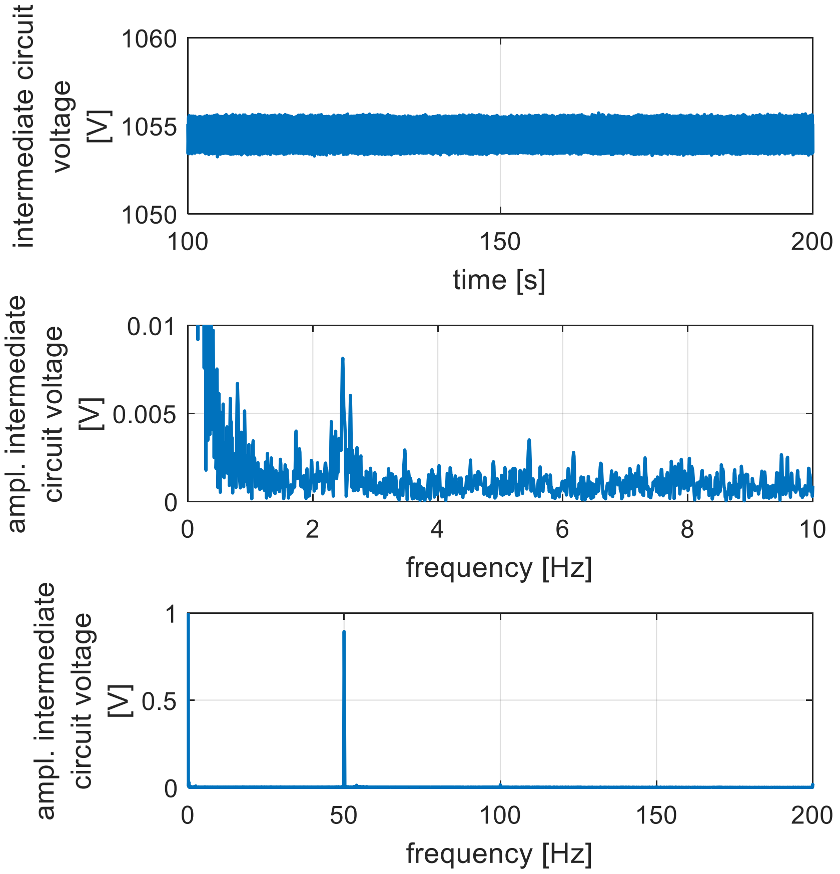

Figure 6: Intermediate circuit voltage for model depth M4 with 16 m/s wind speed and 12% turbulence intensity

5 Summary & Conclusion

This paper shows the approach for the overall wind turbine model consists of aeroelastic model of the blades, the drivetrain model, generator model, converter model and grid model. Above those model the turbine controller is set up and included in the simulation model. The turbine model allows to analyze the impact of the rotor and drivetrain model on the electrical properties.

To represent the first two torsional eigenfrequencies a three-mass-oscillator in combination with the elastic blade model is required.

The mechanically excited natural frequencies of the drivetrain are equally reflected in the FFT of the electrical power fed into the grid. The additional 50 Hz oscillation superimposed in the electrical power results from a dc component of the grid current in the range of several 10 Amperes. This dc component is caused by the grid current controller which is not inside the scope of this paper. The 50 Hz oscillation is only visible at the grid side and is, thus, not associated with the mechanical drivetrain. According to current knowledge, a negligible feedback (see Figure 6) of the electrical variables to the mechanical variables is to be expected due to the rigid dc-link voltage. However, fluctuations in the mechanical power caused by vibrations are almost completely fed into the grid as active power.

The dc-link voltage can therefore be assumed to be constant in the frequency range relevant for the mechanical drivetrain, so that the mechanical and electrical models are decoupled for sensitivity analysis. Far-reaching simplifications are therefore possible for the inverter model and will be included in the overall wind turbine model in the next step.

6 Acknowledgements

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