Torsional vibrations in multi-megawatt wind turbine induction generators

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Contents

1 Abstract

For the development of modern wind energy systems a very short planning horizon is necessary, to keep up with the fast progress in this industrial sector. Therefore, efficient system models and precise models of components of the drive train are required. To evaluate and improve the behavior of the entire drive train, the interfaces between different drive train components have to be considered, to accurately simulate the dynamic behavior of the system. The progress in the modeling process concerning dynamic interaction between all drive train components allows the reduction of strains in the system resulting in a lower system failure ratio.

The generator, as electromagnetic energy conversion system, is the central component, which receives, produces and transfers torsional vibrations, which have to be analyzed via detailed electromagnetic structure dynamic models concerning harmonics.

In this paper a model concerning torsional vibrations in the generator is developed. The influences of other drive train components are studied as well as the dynamic behavior of the generator is considered for typical operating modes of the wind energy system. The analyzed generator is an induction machine with 2.75 MW rated power and a pole pair number of 3. The machine has a rated speed of 1100 rpm and a rated torque of about 25 kNm. The model considers harmonics to describe parasitic effects in the generator. Additionally, influences of the converter and the gear are considered by a dynamic interface in the model.

The simulation results will be validated with test bench measurements at the Center for Wind Power Drives (CWD) of RWTH Aachen University.

2 Introduction and Motivation

The reliability of wind energy systems depends on the failure rate probability of the electro-mechanical drive train and its components [FAU11]. This paper, however, does not examine other influences, such as damages to the tower or foundation [SZI07], burning scenarios [WIN05] or assembly faults. The torsional vibration in the drive train is a well-researched topic in numerous publications [MAR16].

The modeling process of electromechanical drive trains has undergone a fast progress in the last decades due to very detailed models of the drive train components as well as powerful clusters of data processing systems. For example in [MAT16] and [SCH07] the modeling of a wind energy system drive train is introduced with focus on multi-body system simulation with 3D finite element simulation to flexibly describe the deformation of the entire wind energy system in all degrees of freedom.

In this paper the focus lies on the modeling of vibration phenomena between the mechanical and the electromagnetic part of the drive train. With the introduced model a specific transient excitation in the electrical machine and its bidirectional influences are studied. By realizing a bidirectional coupling of mechanical and electromagnetic systems of the drive train, the vibrations in the drive, which exceed a specific component, are identified. This improves the design of these drive trains and increases the reliability of the wind energy system.

The steady state operation generator model with harmonics is combined with a transient operation generator model, which both are described later in this paper. The mechanical model part is adapted with a three mass oscillator. Finally, the electromagnetic model part is transformed into the mechanical frame of reference by derivation of an electromagnetic spring and damping parameter (chapter 3).

The results are validated with test bench measurements performed at the system test bench of the Center for Wind Power Drives (chapter 4).

3 Design of the torsional vibration model

The model of the drive train is based on a wind energy system, which is constructed for the project “FVA-Gondel“. Partners in this project are the Center for Wind Power Drives (CWD) of RWTH Aachen University, the Siemens AG (SI), the Forschungsvereinigung Antriebstechnik e.V. (FVA) and various associated partners. The 4 MW test bench at the CWD is used for measurements with a 2.75 MW wind energy system, including a nacelle with typical control system, a three stage gear with gear ratio of approximately 63 and an induction machine as generator.

The model of the induction machine is divided into an electromagnetic and a structure dynamic part. The electromagnetic machine model consists of two combined models. An analytical model in steady state operation with consideration of harmonics is used [RIC16]. Studied effects are winding harmonics, slotting harmonics, eccentricities or harmonics due to other components of the drive train, which influence the generator’s behavior. The model is validated with measurements in stationary operating points, which is described in chapter 4.

The second electromagnetic model part is described in figure 1. It is built in an environment in MATLAB/Simulink. The model is based on a transient description of the fundamental wave behavior with a nonlinear differential equation system [BIN12]. For each relevant harmonic, which is identified with the model concerning harmonics, a parallel model line is added in this model. Beside various machine parameters, for example the inductances L and resistances R for each harmonic, the input value of the model is the voltage distribution, which is measured on the test bench presented in chapter 4. With a frequency analysis of the voltage, different harmonics are calculated and arranged into the lines of the model. With the d-q coordinate transformation each line is transformed into a two phase system with two axes, which are perpendicular to each other. The differential equation system is calculated independently for the fundamental wave and each harmonic. With equation 1, the electromagnetic torque M_{el} is calculated for each line and superposed. For the current calculation a transformation back to a symmetric three phase description is performed and the specific currents of each harmonic are superposed. With the extended fundamental wave model the transient torque distribution is simulated, which is adapted to the structure dynamic model.

For the structure dynamic model, a three mass oscillator represents the mechanical part of the drive train, including the machine of the test bench, a non-torque load unit for dynamic wind loads in all 6 degrees of freedom and the device under test. A detailed description of the test bench and the identification of the model parameters are shown in chapter 4. The smaller level of detail of the mechanical part allows to study the internal interdependency between mechanical and electrical vibration with the objective to calculate electrical spring and damping parameters which are combined with the three mass oscillator.

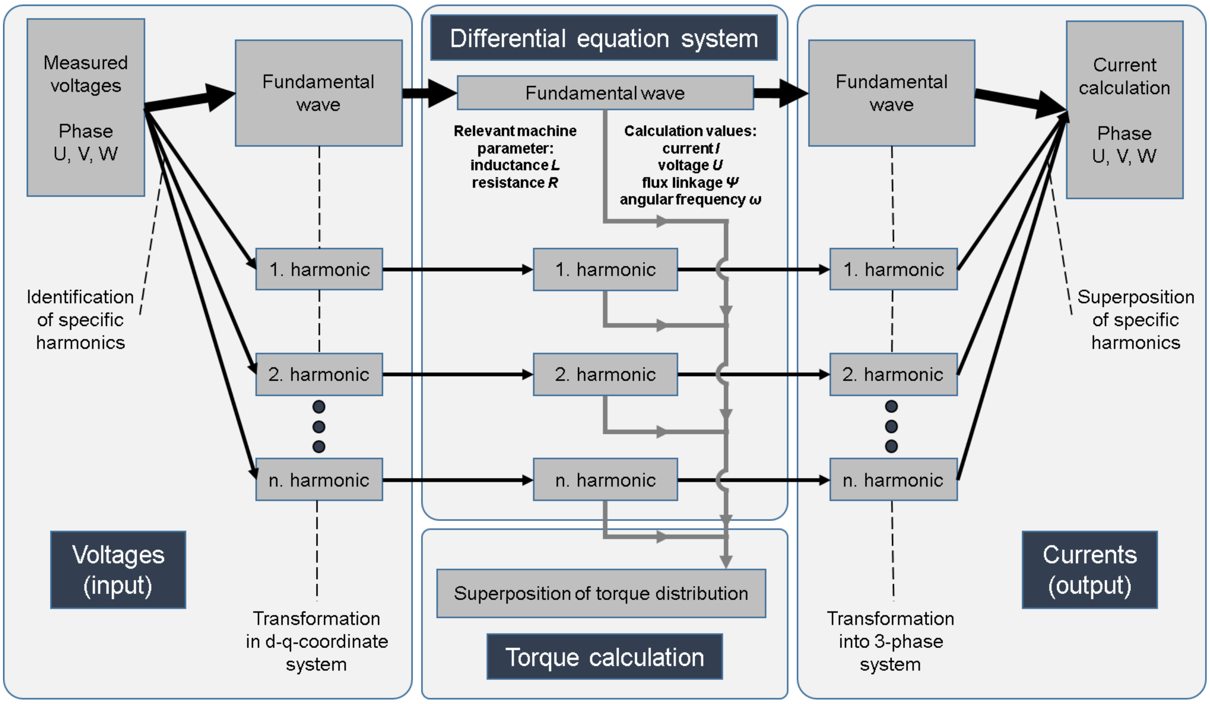

Figure 1: Structure diagram of electromagnetic model part of the torsional vibration model to simulate the transient behavior of the generator.

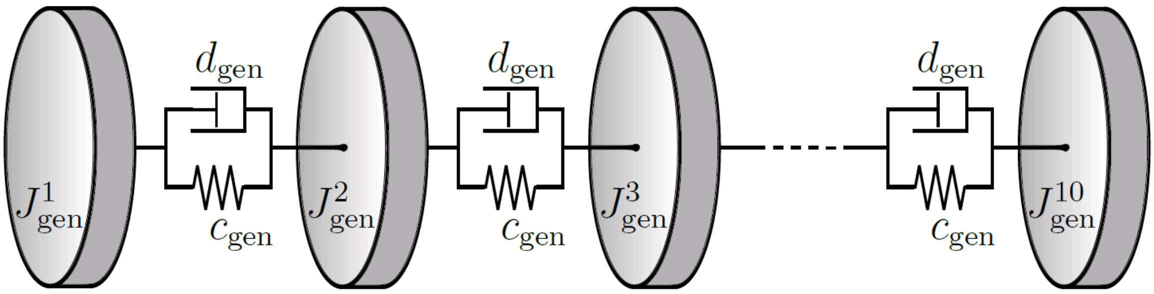

Figure 2: Detailed modeling of the generator’s rotor by division into slices along the length of the machine. Adaptation with spring constant c_{gen} and damping constant d_{gen}.

The differential equation 1 describes the torsional movement of the generator, depending on the electrical torque M_{el}, a load torque M_L at the generator, the number of pole pairs p and the moment of inertia J of the generator's rotor.

$$\frac{\partial\omega}{\partial t} = \frac{p}{J} \cdot [\underbrace{p \cdot (\Psi_{d1} \cdot i_{q1} - \Psi_{q1} \cdot i_{d1})}_{M_{el}} - M_L] \qquad \textbf{Eq. 1}$$

The detailed modeling of the rotor of the generator allows the identification of the torsion of the rotor, comparable to a torque rod (see figure 2). To describe the structure dynamic behavior of the wind energy drive train corresponding to the system test bench at the CWD, a reduced model of the system is designed as three mass oscillator (see figure 3). The three moments of inertia J_1, J_2 and J_3, the two spring constants c_1 and c_2 and the two damping values d_1 and d_2 are calculated analytically and compared with multi body simulation results and test bench measurements performed at the CWD in the project FVA Gondel [MAT16].

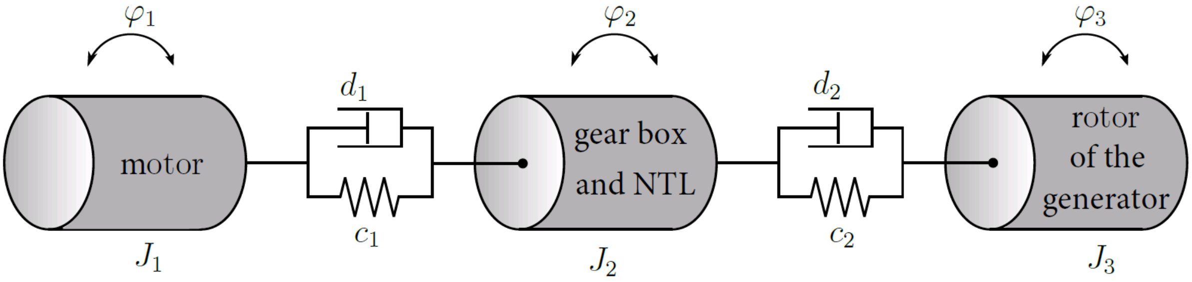

Figure 3: Three mass oscillator describing the test bench with a direct drive permanent magnet synchronous machine (J_1) a combination of non-torque loading unit (NTL), main bearing and 3 stage gear (J_2) and the generator (J_3) of the wind energy system.

3.1 Generator model description

The level of modeling of the electromagnetic model concerning harmonics is very detailed [OBE70]. Influences of the winding harmonics are considered permanently due to the design of the model [RIC16]. The number of considered harmonics is adjustable and tested for frequencies up to 2 kHz. The slotting harmonics are considered with a permeance function, which is calculated with conformal mapping. The effects occur for the higher frequencies - first slot harmonic for 1.5 kHz at nominal conditions – and for higher calculation time. Therefore, the influences of slotting are neglected in the next analysis steps. The eccentricities are considered with objective functions, adding corresponding harmonics to the magnetic field distribution. Due to longer calculation time, these parasitic effects are also excluded in the next modeling steps. The effect of non-sinusoidal voltage distribution, due to the influences of the converter, are considered by an analysis of the voltage harmonics and then integrated into the matrix calculation of the voltage equations.

The extended transient electromagnetic model of the generator is tested for selected harmonics. The harmonics are chosen, relating to their amplitude, and considered by calculation of the resistances and inductances of the specific harmonics. The amplitudes of the most relevant harmonics are less than 10 A, considering nominal operation conditions, whereas the amplitude of the fundamental wave is about 2.5 kA. For this reason, these effects are firstly excluded from further analysis in this paper.

The modeling of the generator's rotor with several slices has been tested concerning the structure dynamic behavior. The difference in the simulation of the torque of the generator is very small and neglected in further analysis. However, the individual calculation of the torque distribution for every slice, explained in [MAT16], and a variation of the spring and damping constants between the slices is performed in further work.

3.2 Combination of electromagnetic and structure dynamic model

In many state of the art electromechanical drive train models, a typical one direction coupling between the electromagnetic and the structure dynamic model parts of the drive train is considered. In these cases, the focus is on one of these working areas, while the other one is treated as excitation or boundary condition. For example, for a detailed analysis of the vibration behavior of a gear box, the generator is modelled as an influencing torque, working on the high speed shaft (HSS) of the gear box. The other way round, for a generator model, often the gear box is only considered as a load torque, working on the generator. In contrast to these models, the presented model in this paper is bidirectional, which means, that, for example, an excitation of the gear box to the generator results in a feedback to the gear box, reaching to an additional excitation and so on. Due to the fact that structure dynamic models and electromagnetic models are both oscillating systems with different types of oscillators, the idea is to couple these models by transformation of the behavior of one system to the type of oscillator of the other system. For this reason, the electromagnetic behavior is transformed into a structure dynamic spring parameter c_{el} and damping parameter d_{el}, which is adapted to the moment of inertia of the generator's rotor and on the other side to a fixed barrier (figure 4). The barrier represents the electrical system of the drive train, which is handled in this model as infinite stiff.

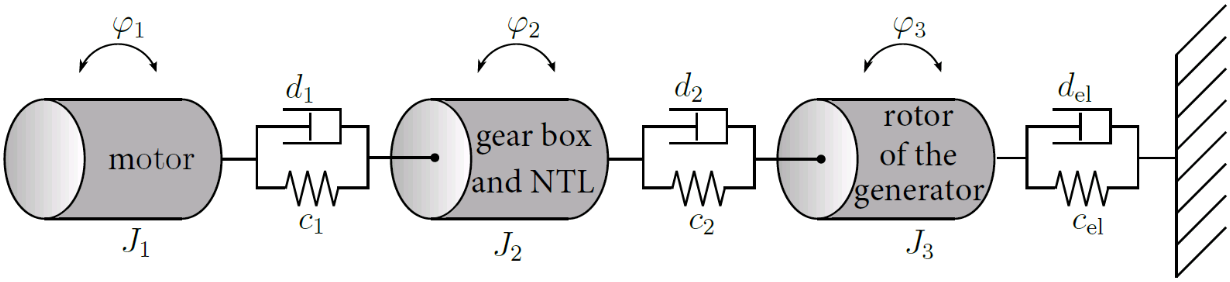

Figure 4: Three mass oscillator with adaptation of electromagnetic spring parameter c_{el} and electromagnetic damping parameter d_{el}. Influence of bidirectional coupled converter system and grid connection is neglected.

With the calculation of a torsional spring, depending on the electromagnetic torque M_{el} and the mechanical angle φ_{mech}, the electromagnetic spring parameter results in

with the breakdown torque of the induction machine M_{bd}, the electrical angle φ_{el} and the

$$c_{el} = \frac{\partial M_{el}}{\partial \varphi_{mech}} = \frac{\partial M_{el}}{\partial \frac{\varphi_{el}}{p}} = p \cdot \frac{\partial M_{bd} \cdot \sin(\varphi_{el})}{\partial \varphi_{el}} = p \cdot M_{bd} \cdot \cos(\varphi_{el})\,, \qquad \textbf{Eq. 2}$$

number of pole pairs p [JOR69]. The number of pole pairs is a design parameter of electrical machines, the breakdown torque is given through the voltage and the frequency for a fixed geometry of the machine and the electrical angle is a consequence of the operating point of the machine. The damping parameter is derived from a theory explained for synchronous machines with damping cage [JOR70]. The damping parameter results in

$$d_{el} = \frac{M_{el}}{s} \cdot \frac{p}{\omega_{mech}}, \qquad \textbf{Eq. 3}$$

with the electromagnetic torque M_{el}, the corresponding slip s, the number of pole pairs p and the mechanical angular frequency ω_{mech}.

The simulation with consideration of the three mass oscillator and the combined electromagnetic and structure dynamic model is shown in figure 5. In contrast to a single moment of inertia for the generator, the three mass oscillator shows other frequencies, especially in the first 0.5 seconds of the simulation.

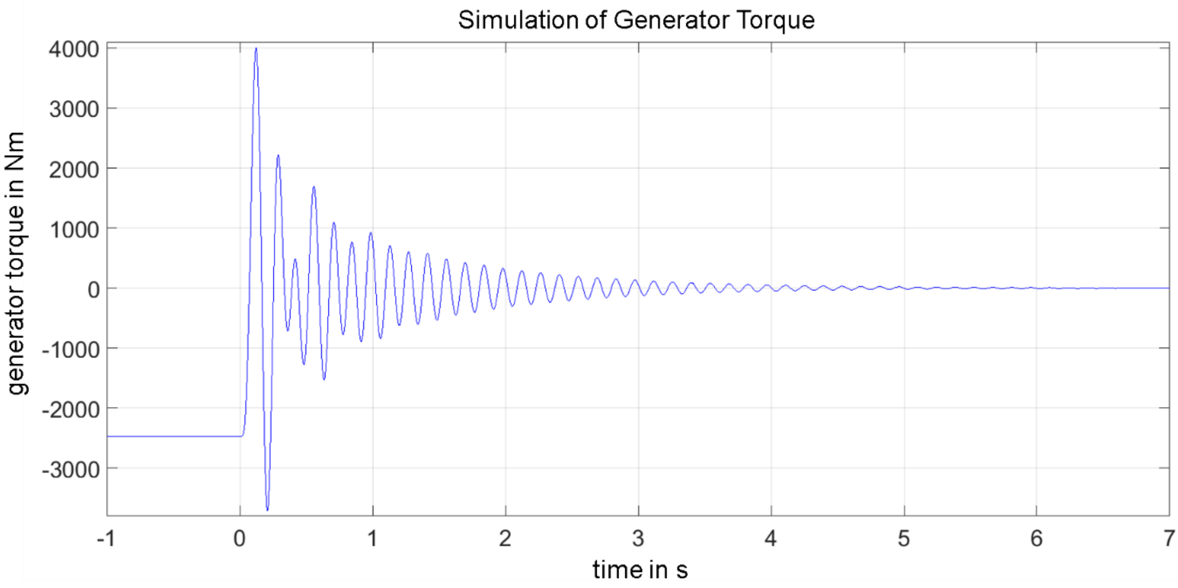

Figure 5: Simulation of the torque of the generator. Response of a load rejection starting with 10 % of nominal torque. Consideration of three mass oscillator for the structure dynamic part of the model.

4 Measurements and Validation

The validation process is divided into three steps. In the first step the model is evaluated for stationary operating points to validate the model parameters, for example resistances, inductances, temperature behavior and stray flux parameters. In the second step the influences of harmonics are studied. In the third step, the transient reaction of the drive train is analyzed.

4.1 Test bench at the Center for Wind Power Drives

Figure 6 shows the 4 MW system test bench of the Center for Wind Power Drives, including a permanent magnet synchronous machine as direct drive motor and a non-torque loading unit to realize a high dynamic force excitation corresponding to the wind. The device under test is a wind energy system with nacelle, main bearing, gear box, generator and converter.

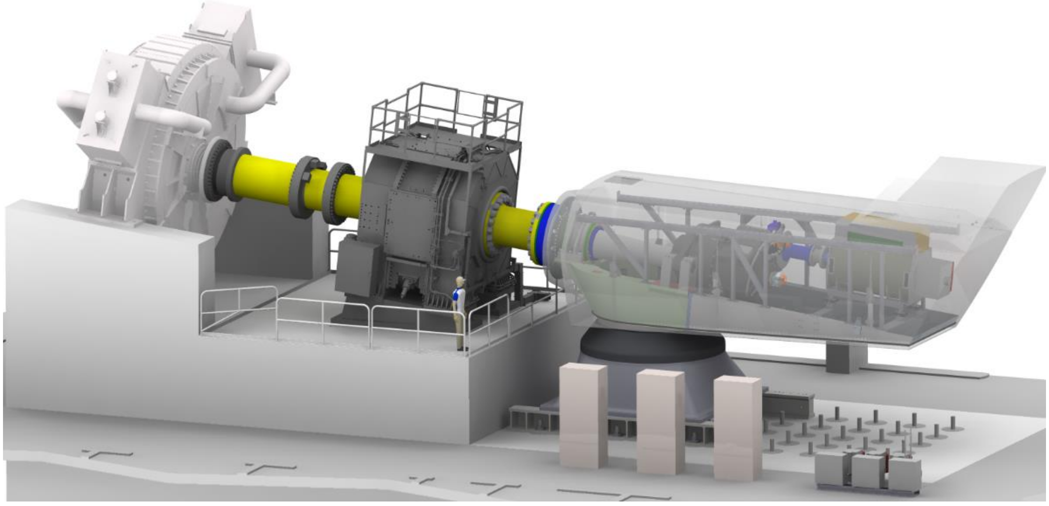

Figure 6: 4 MW system test bench at the Center for Wind Power Drives. Testing of the “FVA-Gondel”.

4.2 Sensor setup for the generator

For the validation of the generator model, a set of sensors is used. Most important sensors are a torque measurement shaft, a speed sensor, voltage measurement, current transformers for stator and rotor currents, temperature sensors and vibration sensors.

4.3 Measurement results and model validation

Figure 7 shows the evaluation of the stator current for the parameter validation of the model. The measurement curve is shown in blue, the simulation result with model concerning harmonics with a sinusoidal voltage behavior is depicted in yellow. The simulation results with consideration of harmonics in the voltage, which are measured on the system test bench are shown in red. The identification of the amplitudes of each harmonic is improved with the consideration of harmonics in the voltage contribution.

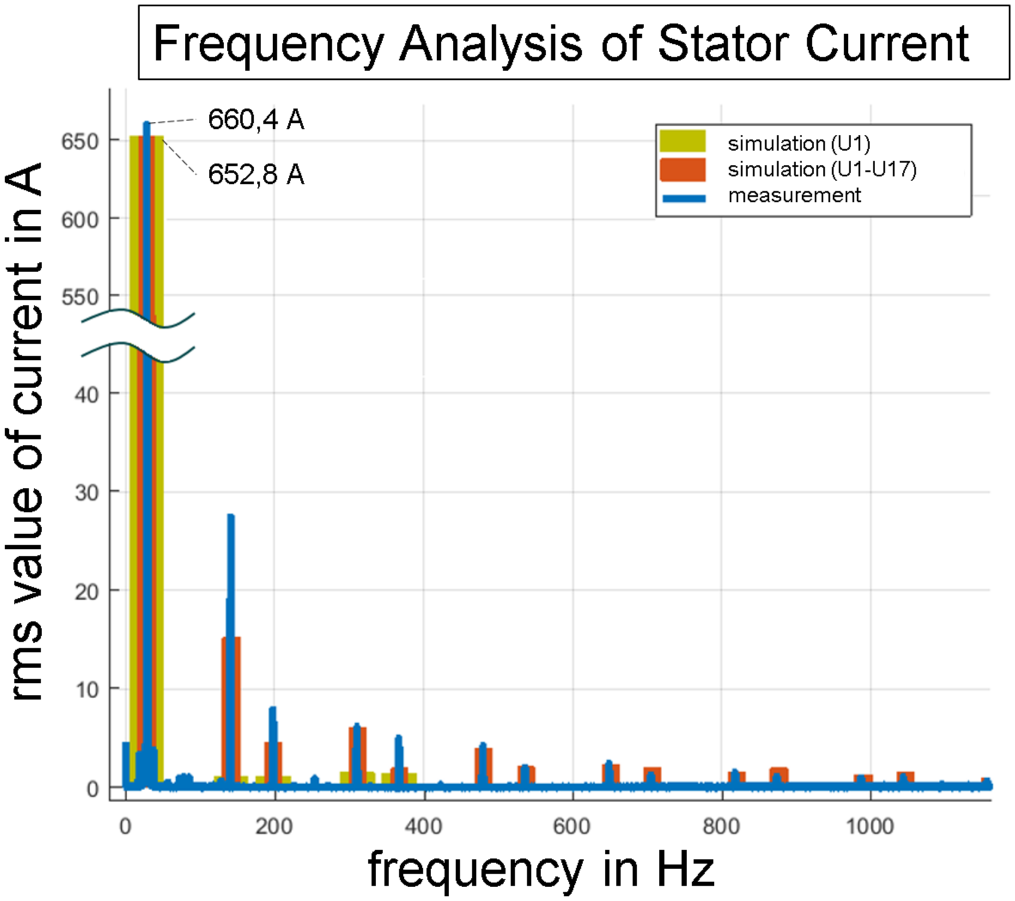

Figure 7: Frequency analysis of stator current for 565 rpm and 10% of nominal torque. Measurement results (blue). Simulation with generator model and sinusoidal voltage (yellow). Simulation with voltage distribution with harmonics (red).

5 Conclusions

The improvement of the interface of electromechanical and structure dynamic models for induction generators is relevant to describe the system behavior of wind energy drive trains. This paper introduces a generator model with two combined electromagnetic field calculation parts and a bidirectional coupling to a multi mass oscillator to describe the interaction between electromagnetic and structure dynamic effects in the wind energy system. The transformation of electromagnetic equations of the generator into a mechanical environment with electromagnetic spring and damping parameters is outlined. The paper also presents the first measurement results conducted at the test bench at the Center for Wind Power Drives are presented.

For future work, the transient behavior of the generator model will be validated with test bench measurements. The interaction between other components of the drive train, for example the gear box and the converter are studied, by extending of the model into a combined model of all drive train components. The model is designed to simulate the system behavior of a wind energy system under typical operating conditions. Therefore, the analysis of system failures, for example Fault Ride Through (FRT) are studied.

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