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2016 J. Phys.: Conf. Ser. 753 082034

(http://iopscience.iop.org/1742-6596/753/8/082034)

Coupling of electromagnetic and structural dynamics for a wind turbine generator

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Abstract. This contribution presents a model interface of a wind turbine generator to represent the reciprocal effects between the mechanical and the electromagnetic system. Therefore, a multi-body-simulation (MBS) model in Simpack is set up and coupled with a quasi-static electromagnetic (EM) model of the generator in Matlab/Simulink via co-simulation. Due to lack of data regarding the structural properties of the generator the modal properties of the MBS model are fitted with respect to results of an experimental modal analysis (EMA) on the reference generator. The used method and the results of this approach are presented in this paper. The MBS model and the interface are set up in such a way that the EM forces can be applied to the structure and the response of the structure can be fed back to the EM model. The results of this co-simulation clearly show an influence of the feedback of the mechanical response which is mainly damping in the torsional degree of freedom and effects due to eccentricity in radial direction. The accuracy of these results will be validated via test bench measurements and presented in future work. Furthermore it is suggested that the EM model should be adjusted in future works so that transient effects are represented.

1. Motivation

A wind turbine is a complex system consisting of highly flexible components such as rotor, main frame and tower. The low eigenfrequencies of those components are within the excitation spectrum of the wind loads and are strongly coupled and thereby represent a system susceptible to vibration. Due to the instationary and turbulent nature of the wind, the high loads in all six degrees of freedom that a rotor couples into the drive system and the influence of the electromagnetic system and grid, load calculation for wind turbines and their components is challenging. To avoid outages due to failures from design deficiencies, simulation models are needed that can calculate those loads while taking above mentioned effects and system wide reciprocal influences into account. Therefore entire system models are developed and investigated. These models are validated with different measurement campaigns on a 4 MW system test bench [1].

One important matter of interest is the representation of the coupling of the mechanical and the electromagnetic system to understand its impact on the drivetrain dynamics, loads and damage cases. To take the reciprocal influences of the mechanical and the electromagnetic system into account a model interface of a generator model consisting of a MBS and an EM model is developed and first results will be presented in this contribution.

2. Outline

For the modelling of the generator in entire wind turbine models the focus usually is on the electromagnetic side thus EM models, mostly for control strategies as in [2] and [3] or to determine the interaction with the grid as in [4]. There, the interdependency is either not considered or taken into account via reduced order models. Even if more sophisticated models are used, mostly to determine the influence of grid faults on the loads of the mechanical drive train as in [5], the coupling usually is just in one direction. The aim for this study is to establish a model interface which represents the application of the EM forces on the generator structure and the feedback of the response of the structure on the force generation. Therefore a MBS model of the generator structure in Simpack is coupled with an EM model in Matlab/Simulink via co-simulation. The EM and the MBS model are adjusted to enable the communication via the interface. The focus of this contribution is on the MBS model of the generator. Therefore the generation of the MBS model is discussed first in section 3.2. Secondly, the design of the force application points in order for the interface to be able to represent the interdependency properly is presented. In section 3.3 the EM model is discussed and the setup of the co-simulation is presented. In section 4 the results of several simulation run ups are presented to show the possible benefits of this modelling approach. Finally conclusions and a brief outlook are given.

3. Modelling

3.1. The reference generator

The considered generator is a three phase induction machine with a wound rotor. The rotor winding is shorted in the junction box to include a current transformer in the rotor circuit, while connecting the stator winding of the generator to a full-scale converter. It has a rated power of 2.8 MW and weighs about 9 tons. The rated torque is 24.7 kNm for a rated speed of 1100 rpm. The number of pole pairs is 3 and the generator has 72 stator and 90 rotor slots with a screwing in the rotor. This leads to higher slot harmonics starting with more than 1600 Hz for nominal operation. A two layer winding scheme to reduce harmonics of the winding is integrated.

3.2. MBS model

3.2.1. Model structure of the MBS model. A MBS model of the generator was generated in SIMPACK to represent the mechanical part of the machine in six degrees of freedom. In order to identify a meaningful level of detail and to make sure that all important masses and stiffness characteristics of the generator are modelled a number of FE models were set up to determine the relevance of the masses and stiffness characteristics of all components. The results showed that the modal properties of the rotor including shaft, bundles of lamination and winding structure, the stiffness of the bearings and the modal properties of the stator and housing structure have large impact on the dynamic behaviour of the generator and should therefore be modelled. The stiffness characteristics of the bearings consisting of two cylinder roller bearings and one deep groove ball bearing for axial forces was calculated using the manufacturer's specifications and implemented using simple spring damper force elements. To represent the modal properties of the rotor and the housing structure including the stator the FE-models of these components were modally reduced using the Craig-Bampton Method [8] and integrated into the MBS model [13]. A special approach was taken to generate these FE-models which will be discussed elaborately in the following subsection.

Furthermore, in order to represent the dynamics of the whole turbine thus its first two eigenfrequencies while not exceeding reasonable simulation time the rest of the drive train was modeled as two lumped masses connected via spring damper force elements resulting in a reduced three mass oscillator for the whole model. This was derived from a detailed MBS model of the turbine which includes all relevant masses and stiffness characteristics of the drive train including, couplings, rotor blade stiffness and inertia.

At last the connection stiffness of the generator to the machine carrier and the rest of the drive train were modelled to ensure proper dynamic behavior. Therefore the stiffness and damping of the rubber mountings were determined on a linear actuator test bench and implemented via simple spring damper force elements. The connection of the rotor of the generator to the rest of the drive train is realized by a steel lamina coupling. Therefore in a first approach it was assumed that the transmission of forces and bending moments can be neglected. Only the rotational stiffness was represented, again via a spring damper force element.

3.2.2. Fitting of the modal parameters of the flexible structures. For some of the generators properties no proper modelling methods were available and a lot of the structural properties were either unknown or could not be revealed due to confidentiality. Thus the material properties of the adhered bundles of lamination of the rotor, the setup of the windings, the detailed tooth geometry and the surface coating of the rotor cage were not known and methods to model these are either highly sophisticated or laborious. Therefore a special approach was taken to create modally reduced FE-models with the proper modal properties.

Since those properties could not be determined due to above mentioned reasons, an experimental modal analysis (EMA) was conducted on the reference generator and the FE-models have then been fitted to represent the measured model properties.

With the modal analysis only modes up to a range of around 300 Hz could be determined clearly, mainly due to the large and complex structure of the generator. A FE-model of the generator with the basic properties of the structure represented was built beforehand and could be used to determine which modes would likely have to be excited and measured.

The mode shapes of the EMA were then compared to the mode shapes of the FE-model, both via visual comparison and using the Modal Assurance Criterion (MAC) [9]. Several characteristic modes were found in both the measurements and the model results, for example the first bending mode of the rotor and the first torsional mode of the rotor which are shown in figure 1. As expected the modes showed some deviations from each other as was expected due to the insufficient modelling methods used for the FE-model. Through adjustment of the stiffness properties of the anisotropic modelled material in the FE-model and application of additional masses and inertia the modal properties of the FE-model were then fitted to match those measured. To do this in a meaningful way only such adjustments were made that correspond to properties of the generator neglected in the modelling process so far. To account for the adhered bundles of lamination of the rotor the shear and Young's modulus of these bundles were adjusted by choosing corresponding anisotropic material properties in the FE-model. To account for the copper cage of the rotor the Young's modulus of the shaft was adjusted and masses and inertias based on the mass distribution of the cage were applied along the rotor and its ends.

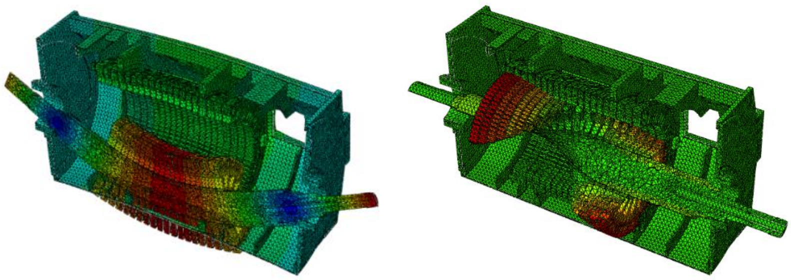

Figure 1: First bending mode at 77 Hz and first torsional mode at 222Hz.

The resulting FE-models were then modally reduced and integrated into the MBS model. To qualify the method and the reduction process the modal properties of the obtained MBS model were compared to the measurements. The comparison of the eigenfrequencies of the fitted modes of the FE-model and the measurements is shown in figure 2. Since the modal analysis yielded clear results only up to a frequency of 300 Hz, a qualification of higher eigenmodes is not possible. The model should represent the dynamic generator behavior quite well also at higher frequencies. Yet, when evaluating the results it should be kept in mind that a validation at higher frequencies was not possible due to the limitations of the conducted modal analysis.

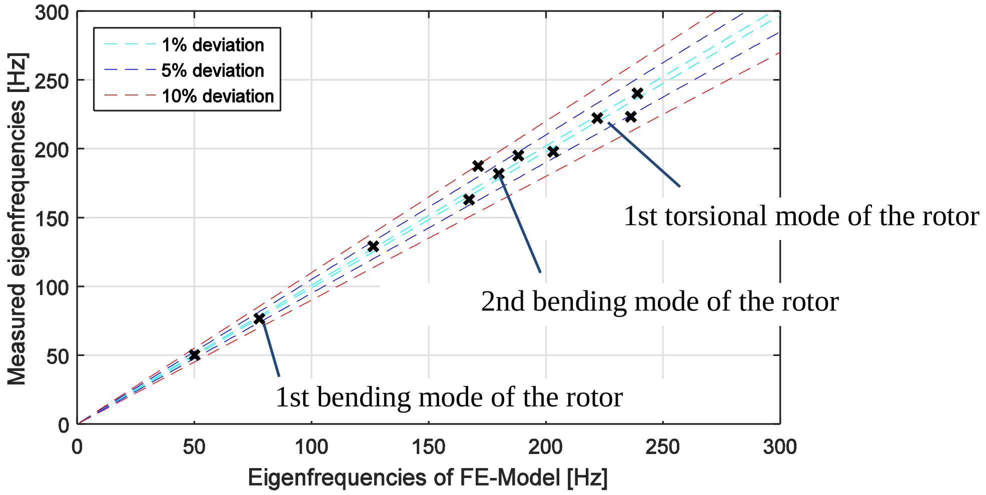

Figure 2: Eigenfrequency comparison of the measurement and the resulting FE-model, key Eigen modes are labeled.

3.2.3. Setting up the interface. In order to be able to apply the electromagnetic forces of the EM model onto the generator structure, the modally reduced FE-models have to be set up with force application points. This is done by defining reference points in the FE-model and coupling them with so called master nodes via constraints [8]. These reference points are then not only used for force application but also to determinate the movement and displacement of the rotor relative to the stator.

The electromagnetic forces have to be applied between the stator and the rotor thus on the rotor with the corresponding reaction force on the stator. Since the EM model is a two dimensional model the rotor and stator were split into several slices along its axes to individually apply calculated forces. In that way axial depending effects such as torsional twist or bending of the rotor can be represented. Figure 3 illustrates this concept with a showcase number of slices. By consideration of the design of the rotor and a subsequent parameter study, a meaningful number of slices thus force application points as well as a suitable type of constraint were determined.

The rotor is built of 20 bundles of lamination. As a result a whole divisor of this number should be taken as the number of slices, since the bundles are rather stiff and any deformation is to be expected between those. Since it is intended to represent torsional effects at least the first two torsional modes should be represented. A parameter study using modally reduced FE-models each with a different number of slices showed that the first and second torsional mode can only be represented by using at least 10 slices. No additional benefit could be found using 20 slices which leads to a final number of 10 slices. The stator was subdivided in the same way.

All surface nodes of the teeth of each slice were coupled with a corresponding reference point on the axis of rotation for the rotor as well as the stator. A continuum distributing coupling, which allows deformation of the coupled surface, was chosen in order to prevent tampering with the modal properties.

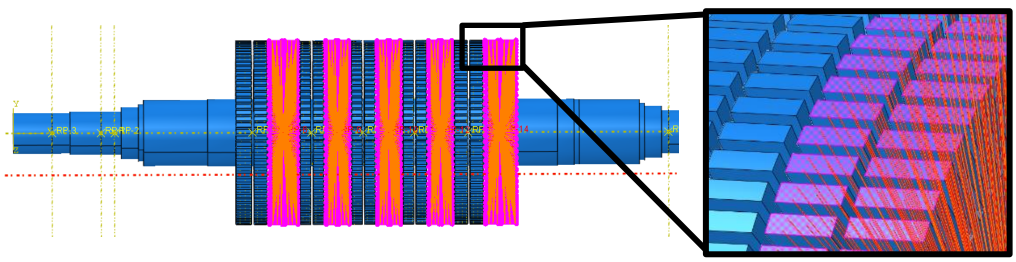

Figure 3: Every other slice of the rotor and coupling of the corresponding surface nodes are highlighted.

3.3. Electromagnetic generator model (EM model).

The electromagnetic force excitation in the generator is described with a 2D analytical model concerning harmonics in the field distribution. The model is implemented in frequency domain and assumes a quasi-static behaviour. Therefore, the magnetic flux linkage is constant and the electromagnetic transient behaviour is excluded. To describe the mechanical transient behavior the relevant instantaneous values of each time step are calculated depending on the output of the MBS model and transferred into time domain.

The electromagnetic model considers parasitic effects of the generator. Harmonics due to the slotting of the machine are included, influences of the winding and eccentricities, for example caused by deviations in the production, are considered.

3.3.1. Composition of the electromagnetic model. Requirement of the EM model on the electrical side is a stationary sinusoidal voltage with specific frequency, describing a constant electrical operating point of the system. The variation of this operating point during the simulation is possible, but not investigated in this paper. Input quantities for the structure dynamic parameters depend on the previously described MBS model. They are introduced in the next section.

The generator is modelled with resistance and inductance matrices, which include rows and columns due to the number of harmonics that describe the parasitic effects in the machine. The values of the resistances and inductances depend on the winding scheme, especially on the number of pole pairs and phases, the number of turns of each specific coil of the winding, the winding factors and the cross-section of the wires. The inductance matrix is divided into self and mutual inductances for the stator and the rotor of the generator.

Inserting the resistance and inductance matrices into voltage equations, the electrical part of the EM model is defined. With the sinusoidal voltage as input parameter, the harmonics of each current in the rotor and stator are calculated [12]. The harmonic currents generate harmonics of magnetic fields in the air gap of the machine. These magnetic rotor and stator fields induce voltages in the rotor and stator relating to the self and mutual inductances. An interdependency between rotor and stator voltage systems is produced. By superposition of the harmonic magnetic field components in the air gap for the rotor and stator, the physical magnetic air gap field, which is described as magnetic flux density, is calculated. Because of the 2D EM model, the flux density is related to the length of the machine and the screwing is described through an analytic function. The axial component of the force densities on the surface of

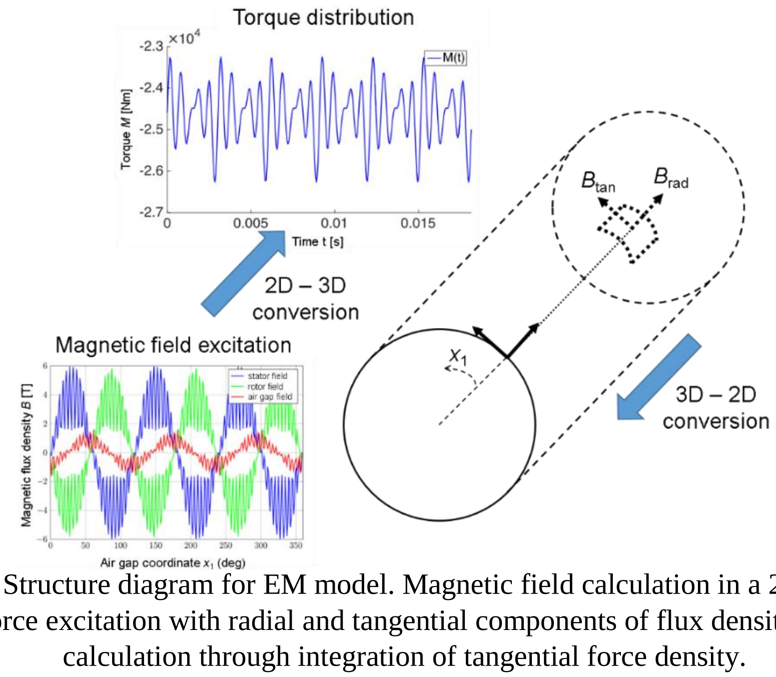

Figure 4: Structure diagram for EM model. Magnetic field calculation in a 2D reference frame. Force excitation with radial and tangential components of flux density *B*. Torque calculation through integration of tangential force density.

stator and rotor resulting of the screwing, is described through an approach of [6]. Other influences for axial force densities in the electrical machine are neglected here. The tangential and radial components of the magnetic fields and force densities are modeled with an approach described in [11]. The resolution in the tangential direction along the air gap is a model parameter. Therefore, the spatial behaviour of the air gap flux density is adjustable due to the mechanical modes, which have to be considered.
The magnetic field in the air gap is separated into a radial and tangential component [11]. In other EM models, often an energy based calculation for the torque of the electrical machine is used. This approach has the disadvantage, that the force density distribution is not calculated locally for each position on the surfaces of rotor and stator. In the presented EM model the force excitation is calculated with the Maxwell Stress Tensor [10], considering radial and tangential components for air gap flux density and force density (see figure 4).

In the next section the interface to the structure dynamic model is introduced. The EM model transfers the actual torque of the generator to the structure dynamic model. In this case the tangential force density on the surface of the rotor geometry is integrated along the air gap and adapted to the air gap radius and machine length, to calculate the resulting torque. The evaluation of the force densities locally for radial and tangential components enables a more detailed interface for the force distribution, which will be investigated in further work of the authors.

3.3.2. Setting up the Interface. The calculated torque distribution of the EM model is fed into the MBS model with a multi-slice-modeling. Thereby, the machine is axially divided into slices of non-screwed machine elements with an offset angle between each other. Therefore, the torque has to be calculated independently for each slice. The offset angle is used as input parameter for the EM model simulation. The current speed of each slice, which is calculated in the MBS model is transferred to the EM model. The speed is important for the operating point of the machine. The slip of each harmonic depends on the relation between current speed of the rotor and speed of the magnetic field.

3.4. Coupling of the EM and mechanical model

As mentioned in the outline the model interface should be able to apply the forces of the EM model on the structure while simultaneously feeding back the response of the structure. To achieve that a co-simulation was set up which allows the MBS model to communicate with the EM model. Simpack offers such a co-simulation interface which allows Simpack and Matlab/Simulink to exchange values via TCP/IP protocol.

Therefore a co-simulation structure as is outlined in figure 5 has been devised. Since the EM model is a two dimensional model a separate instance of the model block had to be set up for each slice. The EM models calculate a torque T_i for each slice of the rotor as well as forces F_i consisting of axial and radial components [7]. These are then delivered to the MBS model and applied to the force application points between rotor and stator. The MBS model in turn calculates rotational speed n_i, angle ϕ_i and displacements x_i y_i and z_i between each pair of force application points and feeds them back to the EM models. In that way the influence of effects such as torsional oscillation, axial twist and eccentricity on the force generation can be represented.

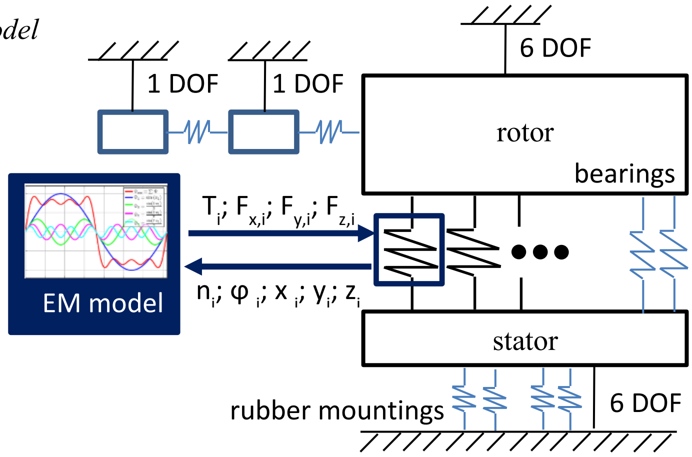

Figure 5: The electromagnetic forces are applied between the stator and rotor via force element for each slice (not all are shown). The mechanical reaction is then fed back to the EM model.

Furthermore a Simulink block was added to the co-Simulation which calculates the voltage and the frequency of the current that is needed for a certain rotational speed. That way any operation point can be induced. This was modelled as a simple Lookup Table without any dynamics from the controller or converter system.

At last a reference model was set up which is identical to the presented model with the exception that it does not feed back the mechanical responses to the EM model. This model will be referred to as the model without feedback and will be compared to the presented model in order to analyse and show the effects of this modelling approach.

4. Discussion of results

Different simulations with the presented model, which will be referred to as the new model, and the models without feedback were conducted, compared and evaluated to qualify the presented model. First of all stationary operation at different operation points was looked at. Then different vibration frequencies the turbine might experience were excited and examined. At last different run ups under load were conducted.

The most dominant effect this new modelling approach presents in the torsional degree of freedom is a damping to any kind of vibration. This can be seen in every simulation conducted. Figure 6 illustrates this effect at nominal operation with an external excitation at the frequency of the second torsional eigenmode of the whole drive train, thus 5 Hz. Seeing that the EM model does not account for any transient effects, this damping was to be expected. Due to the characteristic line of the generator, an increasing in the rotational speed leads to a higher torque which effectively decelerates the drive train contrary to the increase itself. The calculated torque clearly shows a higher activity at this frequency which results from said effect.

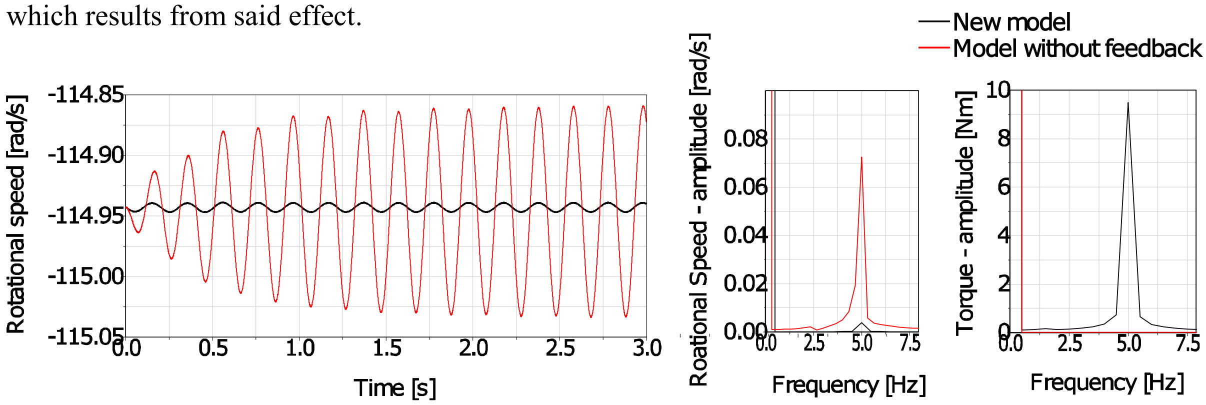

Figure 6: Development of values at nominal operation with an excitation of 5 Hz.

An exception poses the excitations that originate from the EM model itself where the feedback slightly enhances or decreases the resulting vibrations, depending on the operation point. This can be seen clearly at the first harmonic frequency of the winding at 209 Hz at an operation point in partial load of 700 rpm generator speed. Figure 7 shows this effect. If the model experiences an excitation at exactly this frequency, both effects superpose while the damping is more dominant as is shown in figure 8.

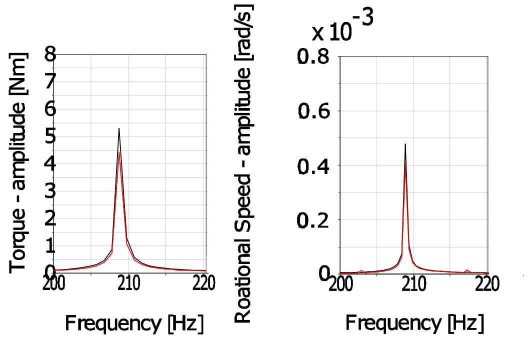

Figure 7: Development of values at 700 rpm with no excitation.

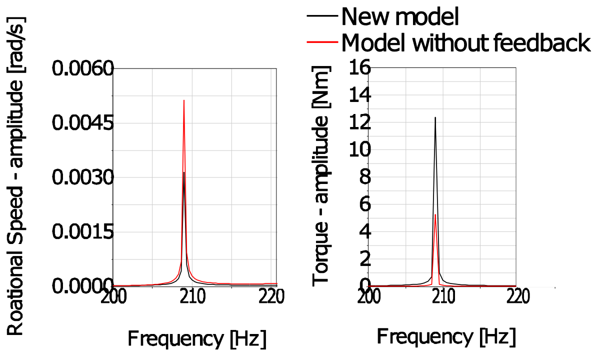

Figure 8: Development of values at 700 rpm with an excitation of 209 Hz.

Another exception poses when an excitation from the EM model hits an eigenfrequency of the mechanical model. This leads to a significant increase in vibration as is shown in figure 9.

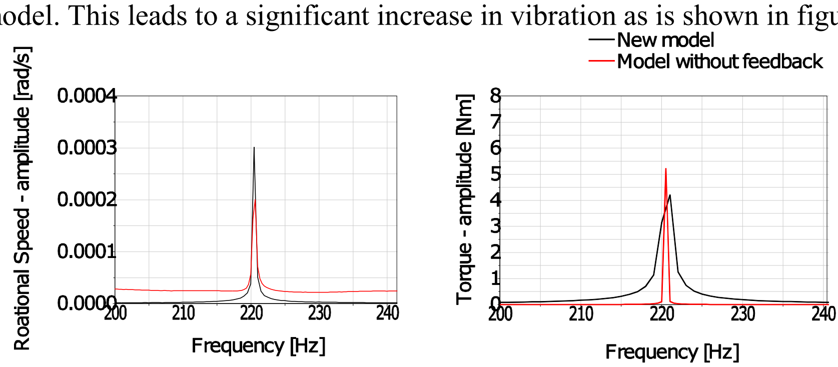

Figure 9: Development of values when the first harmonic frequency of the winding hits the first torsional eigenmode of the rotor of the generator.

The screwing of the rotor leads to an axial component of the air gap forces. Thus the EM model produces an axial force with the same excitation spectrum as the torque. This causes mainly a constant axial force superposed with small vibrations originating from the EM model.

Since eccentricity is considered in the force generation a resulting radial force due to unbalanced magnetic pull from the sag of the rotor is generated. This leads to notably further sag, from a primary sag of 0.1 mm up to a sag of 0.17 mm in nominal operation as is shown in figure 10. Additionally a horizontal displacement can be seen which results to a large proportion from the radial bearing clearance of 30 µm in each direction.

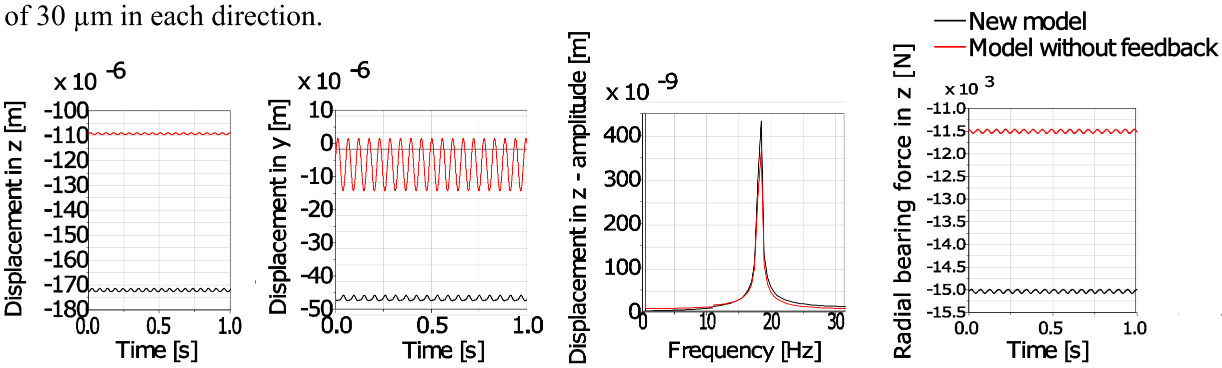

Figure 10: Displacement in the middle of the rotor of the generator in nominal operation and bearing forces due to unbalanced magnetic pull.

All these results illustrate the effects of the separate feeding back of the mechanical responses thus in the rotational degree of freedom, in radial and axial direction. Especially the damping in torsional direction and the massive sag due to radial forces due to eccentricity are relevant. Both the axial and radial forces are represented in the bearing forces as well. Especially the feedback of the eccentricity leads to a 30 % higher radial bearing force as can be seen in figure 10.

Journal of Physics: Conference Series **753** (2016) 082034 doi:10.1088/1742-6596/753/8/082034

In certain operation modes these effects superpose and cause even further excitations for example due to an eigenmode at 18 Hz, which involves radial movement of the rotor of the generator and which is exactly at the frequency of the rotation of the rotor of the generator in nominal operation. Whether this eigenmode exists in the real turbine remains to be validated, yet it will be used here to demonstrate the effects such a mode can have using the proposed model.

As is shown in figure 10, the EM model causes an excitation at 18 Hz in radial direction. The mechanical response of this excitation is then feed back into the EM model which results in an amplitude peak at 18 Hz in the torque and axial force generation as is illustrated in figure 11. These then excite vibrations in torsional and axial direction as is shown in figure 12.

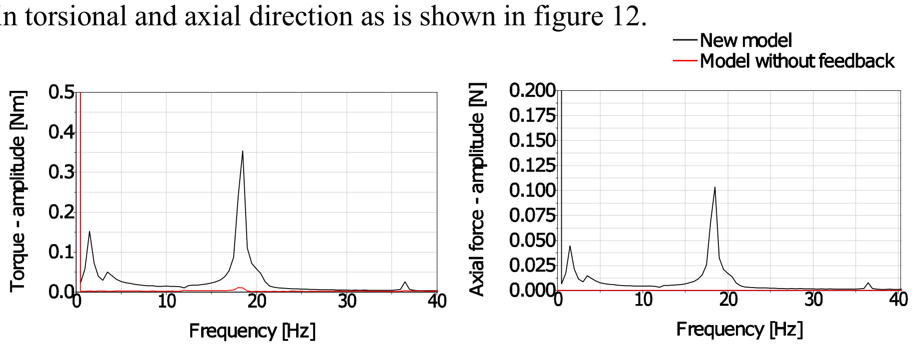

Figure 11: Resulting excitation in Torque and axial force due to feedback or radial vibration.

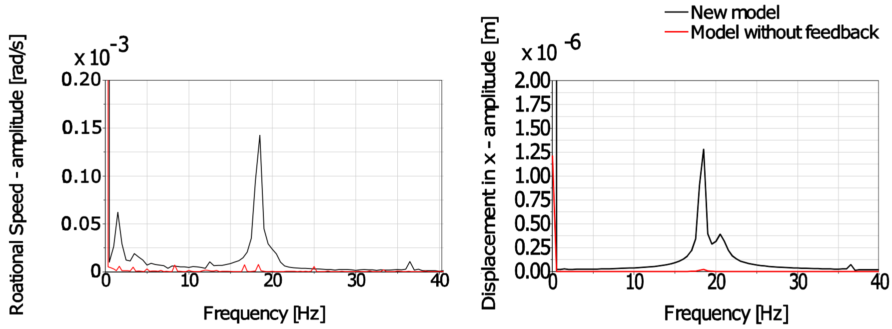

Figure 12: Resulting vibration due to excitation in the electromagnetic force generation.

5. Conclusions and outlook

More sophisticated models which represent interdependent effects between components are necessary to calculate drive train dynamics and loads of wind turbines and subsequently avoid failures from design deficiencies.

Therefore a coupling of a mechanical and electromagnetic model of a generator is introduced to represent the reciprocal effects between the mechanical and the electromagnetic system. The modal properties of the MBS model ware fitted to correctly represent the relevant behavior of the mechanical structure regarding this coupling. Furthermore the interface thus the force application points were devised so that torque, radial forces and axial forces can be applied correctly along the rotors axis. Next an analytical EM model of this generator was set up to calculate these forces taking the response of the structure into account. These models were then coupled via co-simulation.

Simulations were been conducted to validate the plausibility of the model and to check for relevant effects represented by this new modelling approach.

A representative extract of simulation results were presented to show the effects that are taken into consideration with this new modelling method. It was shown that a dominant damping effect occurs in the rotational degree of freedom which was to be expected. It was shown further that axial and radial excitations originating from the EM model cause vibrations which in turn have influence on the electromagnetic force generation. A notable impact on the rotational dynamic of the generator and on bearing forces could be shown.

Thus the model presented matches the intended modelling aim and it was shown that some interdependencies in the electromagnetic force generation of the generator can only be represented by using the proposed model interface.

As a next step the presented modelling method will be extensively validated by measurements at a complete nacelle including drive train on a 4 MW system test bench.

The authors intend to further develop this model and extend the research regarding the modelling of the force generation of wind turbine generators. On the electromagnetic side it is intended to include transient effects in the EM model. Besides that the models will be coupled with converter models to investigate interdependencies of harmonic waves or impact of fault ride through scenarios.

On the mechanical side on the other hand it is intended to include more aspects of the other parts of the drive train to check for interdependencies like for example the high speed shaft gear stage. Furthermore a validation of the MBS model for higher frequencies is eligible to qualify the model for acoustic research. Additionally it should be investigated whether the shown impacts are critical and can cause damage.

Acknowledgments
This research is funded by the German Federal Ministry of Economic Affairs and Energy (BMWi).

Supported by:
Federal Ministry for Economic Affairs and Energy
on the basis of a decision by the German Bundestag

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