Combination of Multi Body System Simulation, Electrical Simulation and Condition Monitoring –
A powerful research development

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Summary
The Institute of Mining and Metallurgical Machine Engineering (IBH) at Aachen University develops in close collaboration with the Institute of Machine Elements and Machine Construction (IMM) of the University of Dresden and in conjunction with several partners of German industry an integrated simulation and multi-sensor condition monitoring system for wind turbines within the project “SIMU-Wind”. Hence all relevant values of a multi-megawatt wind mill have been recorded throughout a year. The data of the reference construction in combination with a detailed co-simulation of the mechanical and electrical components is taken as a basis to develop a new, more accurate condition monitoring system.

Introduction
The SIMU-Wind project is managed by the IBH, Aachen University and the IMM, Dresden University funded by the INNONET research program (Federal Ministry of Economics and Technology and the VDI/VDE Innovation + Technik GmbH). Additionally the following industrial partners are involved:

ACIDA GmbH (CM-systems and CM service)
Centa Antriebe Kirschey GmbH (couplings)
Eickhoff Maschinenfabrik GmbH (gear boxes for wind turbines)
ITI GmbH (multi body system simulation tool)
REpower Systems AG (wind turbines)
SEG GmbH & Co.KG (converter)
Svendborg Brakes A/S (brakes)
VEM Sachsenwerk GmbH (generator)

The goal of SIMU-Wind is to develop a comprehensive multi sensor condition monitoring system in combination with a multi body system and electrical simulation.

Thus, more than 80 sensors for different terms (strain, torque, movement, angle, temperature, current, voltage) has been installed at the drive train and the electrical system inside a 2MW reference wind turbine situated at the north sea coast.
Furthermore a multi body system model of all drive train components and the main frame as well as a detailed electrical simulation model was generated to simulate the system behaviour in different operation situations. The Measurement should verify the modelling for steady state operation as well as for transient conditions and should give a deeper understanding about the dynamic system response in critical situations.

Mechanical measurement

The measurement has been accomplished for a period of ten months (April 2005 to February 2006). At the drive train 64 Sensors were placed at the main bearing, rotor shaft, gearbox, gearbox outgoing shaft and generator as depicted in figure 3 [1].

Additionally 24 strain gauges have been fixed to the housing (main frame, tower and nacelle). Getting to know the state of operation further signals of the control unit (power, wind speed, pitch of rotor blades, nacelle position, brake signal) are stored.

All signals have been sampled with rates up to 1 kHz per channel. All in all each day about 2.5GB had to be recorded on hard disc. One reason for the high number of sensors was to find out correlation between different sensors and the opportunity to substitute certain measurement points. Another aim was to get more information about the drive train behaviour for different wind conditions.

In figure 4 examples for some sensor applications at the drive train are given. All signals were stored and particular transferred to a data base in Aachen. The data acquisition software gives the opportunity to sample characteristic values (rms, min. and max. value, etc.) every five minutes and to store them in a SQL-database. Thus an offline data analysis can be carried out easily.

During the measurement several dynamic break programs have been initialized to monitor the system reaction. Among these are hard breaking situations to analyse natural and resonance frequencies in the drive train elements. These detected frequencies have been used for calibrating the mechanical multi body system simulation.
The stored torque measurement of rotor shaft, generator shaft and the power signal out of the control system are classified and compared in collectives to get information about residual lifetime of drive train elements. In figure 5 the collective of the rotor shaft torque for a short period of time is shown in a standardized diagram.

Comparison between several signals showed a good possibility to substitute sensors and measurement points without loss of information [2].
**Electrical measurement**

To verify the systems behaviour especially during critical operation an electrical measuring system has been developed with prototypes of current sensors at the IBH in cooperation with SEG and ABB Entrelec. This system is able to record data during steady state operation, but especially critical conditions like short circuit and ground faults properly; three phase stator currents of 10kA can be detected without saturation of the sensors, see figure 6. Three phase stator voltages, rotor currents, the converter current and the temperature of the IGBTs is measured as well. The voltage and current signals are of excellence quality. The rotor angle is detected very precisely; a sensor samples 2048 points per revolution. Every channel is sampled up to 10kHz which generates a volume of data of more than 10GB per day.

The knowledge of all relevant currents and voltages as well as the high resolute rotor angle allows calculating the air gap torque without taking the mechanical torque into account. Comparing the mechanical torque on the outgoing shaft of the gearbox with the air gap torque an excellent accordance is achieved, figure 7. In addition this calculated value is suitable for verifications of the electrical modelling.
**Electrical simulation**

The typical concept of generators in wind turbines is the double fed induction generator (DFIG), allowing easily variable speed operation. The rotor is fed by a three-phase variable frequency source split into two voltage source converters linked via a capacitor. These converters (machine side and line side) feed the DFIG rotor with active and reactive power as well as exchanging the power with the grid. By only controlling the slip power in the rotor circuit the converters can be downsized to about 30% of the wind turbine rated output.

![Electrical simulation model](image)

**Figure 8: Electrical simulation model**

The part of the simulation representing the generator is obtained using the voltage equations from the theory of induction machines. Because of different frequencies of stator and rotor values the three phase system is transformed into the rotating reference frame, so called d-q-components. The transformed sinusoidal quantities are represented in the complex plane by a rotating space vector with a frequency 50 Hz. If observing this space vector from a coordinate system which is also rotating at 50 Hz, the space vector appears to be stand still leading to dc quantities.

Figure 9 shows the scheme of the complete electrical model, implemented in Matlab/Simulink. The generator model calculates the electrical gap moment for the mechanical simulation system and gets the rotating speed back for further calculation.
So far this conventional model is suitable to study stationary operations. The common goal of the SIMU-Wind project is to describe the behaviour of all drive train components with transient load. Thus, the model was refined to figure the dynamics that occur during brake events, gust of winds and grid faults. Hence saturation and loss due to temperature are taken into account. Thus, the transient model can be later used as a screening tool in identifying critical contingency scenarios.

The idea of symmetrical components is used as well to analyze unsymmetrical grid faults. As depicted in figure 10 the transformed dq components of each phase are converted into positive, negative and zero sequence components in dq coordinate system. This method gives the contribution of the phases for the grid faults.

For the purpose of validating the model, the input parameters were initialized with realistic measurement data. The output of the simulation is the air gap torque, which is compared with the real existing values. Using a very exact angular position of the rotor the torque can be determined when transforming the measured three phase currents into dq-frame. First model calculations of operation during speed-up, under- and over synchronous operation show good accordance between measurements and simulation.

**Multi body system simulation**

The simulation model contains the mechanical drive train under consideration of the rotor, the gear housing, the main frame and the tower. Furthermore the coupling between tower and main frame is analyzed more detailed over the azimuth adjustment and the azimuth bearing. For relevant components (main frame, main shaft and gear housing) elastic structures will be integrated in the MBS-model.

**Modelling and Discretization**

The drive train model has 22 rigid torsional masses, which are connected with mass less spring-damper-elements. The planetary gearing is modeled explicit and considers the torsion of the planets around another axis.
Additional the periodical changing of tooth meshing stiffness is included so that transient resonance vibration caused by stiffness variation can be identified. The relevant parameters (mass, inertia and stiffness) have been determined from the engineering drawings resp. from the three-dimensional CAD-data.

![Mass discrete drive train](image)

**figure 11: Mass discrete drive train**

After the definition and determination of the parameters first assembly-models for rotor, gearing and the mechanical part of the generator have been created in the particular simulation tools (SimPACK [3], SimulationX [4]) and combined to one drive train model after a successful kinematic verification. This method allows a high degree of replaceability of the components (e.g. different degrees of discretization) and avoids the transfer of modelling mistakes to the complex drive train model. Firstly shear torsion models for the drive train with stiff rotor, rotor-models, as well as models of the drive train with discretized rotor have been developed. Additionally the analysis of variants with an elastic gearing support was done.

After verifying the torsion model axial freedoms have been added for the relevant assemblies. The complete mechanical state of extension contains additionally flexible (elastic) substitute models for the main frame, the main shaft and the gear housing (table 1). Damping factor and load input function were extracted from the measurement results described above and from wind simulation programs.

<table>
<thead>
<tr>
<th>Model</th>
<th>Specification</th>
<th>Kind Of Discretization</th>
<th>Rotor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mod01rb</td>
<td>Rotorblade</td>
<td>Torsion, Stiff</td>
<td>9-Mass-Oscillator (fixed)</td>
</tr>
<tr>
<td>Mod01r3x</td>
<td>Rotor</td>
<td>Torsion, Stiff</td>
<td>9-Mass-Oscillator (fixed)</td>
</tr>
<tr>
<td>Mod01r3x</td>
<td>Rotor</td>
<td>Torsion, Stiff</td>
<td>9-Mass-Oscillator (free)</td>
</tr>
<tr>
<td>Mod01r</td>
<td>Drive Train (AS)</td>
<td>Torsion, Stiff</td>
<td>Stiff Rotor</td>
</tr>
<tr>
<td>Mod01r</td>
<td>Drive Train (AS)</td>
<td>Torsion, Axial, Stiff</td>
<td>Stiff Rotor</td>
</tr>
<tr>
<td>Mod01rta</td>
<td>AS + Gearing Support</td>
<td>Torsion, Stiff</td>
<td>Stiff Rotor</td>
</tr>
<tr>
<td>Mod01rta</td>
<td>AS + Gearing Support</td>
<td>Torsion, Axial, Stiff</td>
<td>Stiff Rotor</td>
</tr>
<tr>
<td>Mod02r</td>
<td>Drive Train (AS)</td>
<td>Torsion, Axial, Stiff</td>
<td>Stiff Rotor</td>
</tr>
<tr>
<td>Mod02r</td>
<td>Drive Train (AS)</td>
<td>Torsion, Axial, Stiff</td>
<td>Stiff Rotor</td>
</tr>
<tr>
<td>Mod02rta</td>
<td>AS + Gearing Support</td>
<td>Torsion, Axial, Stiff</td>
<td>Stiff Rotor</td>
</tr>
<tr>
<td>Mod03mf</td>
<td>AS + Main Frame</td>
<td>MBS, Flexible</td>
<td>Stiff Rotor</td>
</tr>
<tr>
<td>Mod03mf</td>
<td>AS + Main Frame</td>
<td>MBS, Flexible</td>
<td>9-Mass-Oscillator</td>
</tr>
</tbody>
</table>

**table 1: Model overview**

A realistic modelling of the drive train dynamic is only possible with the use of the MBS-method (rigid or elastic), because neither the torsional vibration analysis with its restricted degrees of freedom nor the shear FE-method with its focus on stresses and small deformations in parts can give realistic results to the dynamic
characteristics of the entire system. Therefore relevant assemblies (main frame, main shaft, …) have been integrated into the MBS model of the entire drive train using FE-structures to show the elastic system behaviour. Since a consideration of entire FE-meshes is calculationally not possible due to the number of degrees of freedom, which would be a multiple higher, modal substitution systems with the necessary master degrees of freedom are used [5,6].

Module of wind turbine

The effort for the simulation method, described earlier, is very time intensive and usually not possible to automate. For a simplified application precasted models have to be developed, in which model parts of the drive train are already modelled parameterized. This modular concept of models enables the user, without high expertise on simulation knowledge in the particular physical field, to create correct simulation models. This partly automatic creation of models can give plausible answers on a main part of the problem. Only in the case of special or exceptionally detailed problems the simulation with models, that have to be developed entirely new by an expert, is still necessary. The different mechanical model parts (rotor, gearing and coupling) are shown in figure 12. In the right part of the figure the entire model of the mechanic drive train, composed from the single assemblies, is shown.

Comparison with measured Data

For the verification of the simulation model two different tasks are distinguished. Firstly the proper measuring points for the control have to be found. Therefore FE-calculations have to be made on the according assemblies under defined loads. With the gained measurands the model can be verified and possibly be modified. Because only a model ensured with measurements, is able to provide safe information not only to the normal mode, but also to events, occurring rarely.

<table>
<thead>
<tr>
<th>Rotor-Model</th>
<th>Gear-Model</th>
<th>Drive train model</th>
</tr>
</thead>
</table>

figure 12: Sub-models and mechanical drive train model

Aim of the FEM-calculation is to determine the expansion behavior of the main frame under defined loads. Due to the knowledge of local expansion maxima and minima it is possible to determine proper measuring points for the registration of the expansions. These measured expansions are to be used later for the verification of the created calculation model. In the practical application the main frame is in a preloaded condition (e.g. by the force of gravity of the rotor, the gearing and the generator). To simulate this, the following load model, characterized as “basic loads” has been determined. Thereby the following boundary condition applies still: the tower is fixed.

- No wind, no rotation of the rotor and due to that no torsional load
- Force of gravity of the rotor
- Force of gravity of the gearing
- Force of gravity of the generator
<table>
<thead>
<tr>
<th>Load Number</th>
<th>case-</th>
<th>Basic Load</th>
<th>Load specific load</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>LF01</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td>Torsion around the tower longitudinal axis</td>
</tr>
<tr>
<td>LF02</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td>Bending along frame longitudinal axis</td>
</tr>
<tr>
<td>LF03</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td>Torsion along frame longitudinal axis</td>
</tr>
<tr>
<td>LF04</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td>By nominal torque rotor</td>
</tr>
<tr>
<td>LF05</td>
<td>No</td>
<td>Yes</td>
<td></td>
<td>N10c: Operation by nominal wind (ca. 11-13m/s)</td>
</tr>
<tr>
<td>LF06</td>
<td>No</td>
<td>Yes</td>
<td></td>
<td>N10b: Operation by little wind (ca. 5-7m/s)</td>
</tr>
<tr>
<td>LF07</td>
<td>No</td>
<td>Yes</td>
<td></td>
<td>N10k: Operation near turning-off wind (ca. 23-25m/s)</td>
</tr>
<tr>
<td>LF08</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td>N10k: Operation near turning-off wind (ca. 23-25m/s)</td>
</tr>
</tbody>
</table>

**table 2: Load cases overview**

The basic loads underlie the first four load cases, table 2. For the explanation of the cases only the load specific loads will be described in the following.

Four load cases are defined (LF01 to LF04) from which it is expected that they have a significant share on the deformations of the main frame. Based on this calculated results a pre-selection of expansion measurement points was made. The cases LF05, LF06 and LF07 are based on real measurements. They have been used for the verification of the pre-selection of the measurement points and the determination of additional expansion measurement points. The load cases LF07 (operation near turn-off wind) and LF08 (reference load case) were used for the determination of the relevant measurement range. With the resulting measurement points the bending and torsional behaviour has to be estimated.

To gain reliable simulation results it is mandatory to verify the calculated values with measurements.

The first measurement results after the startup and verification of the measuring setups on the reference turbine are available within the scope of the research project. Next to the torques further important measurements are gathered for the adjustment of the simulation model. Due to that, not only the deformations of the main frame (expansion with strain gauges), but also the axial displacement of the single shafts and the entire gearing- and generator housing regarding the main frame can be analyzed.

For the verification of the quality of the model these measuring results are compared to the according sensor signals on the model and evaluated. Only in the following simulation calculations can be made to different load cases on the model.

**Further steps**

After finishing the measurement the alignment of the measured data with the simulation results is the next step. Additional the electrical and the mechanical model will be combined to a complete model and tested. The condition monitoring system will be build up with a minimum of necessary sensors fulfilling the requirements of the German insurance regulations. The analysis tool will be combined with the simulation model, so that results of the simulation can be implemented into the analysis of the actual system stage.

Therefore the allocation of the potential and the kinetic energy for the individual critical mode shape has to be analyzed. An exact Campbell-diagram of the analysed wind turbine, in which the natural frequencies and the excitation frequencies (e.g. tooth excitation forces of the different steps or the multiple of the rotor rotation speed 1p, 3p and 6p) are plotted over the rotational speed, can be defined with critical operating ranges.

Furthermore calculations in the time domain will be made for defined load cases (normal mode by different wind velocities, start and stop of the turbine, emergency-stop, …) with the created model.
Literature


