Analysis and Application of Hardware in the Loop Wind Loads for Full Scale Nacelle Ground Testing

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Abstract

The advancement in wind energy is a main aspect of the German "Energiewende", the switch from conventional power production to renewable energy sources. With wind as the energy source with the highest potential wordwide one challenge in this process is the improvement of the reliability and availability of wind turbine generators (WTG). Because of the lack of long term experience with multi megawatt WTG, several research institutes and OEMs are building up test benches to close that gap in knowledge. To operate these test benches standard test procedures are needed. In this paper we explain in the first section why there is a demand for WTG system test benches especially using advanced testing methods. The second part deals with the interfaces for the full size ground test, focussing on the application of mechanical wind loads on the drive train. To apply realistic wind loads the rotor system is integrated as Hardware in the Loop (HIL) component in the test application. Therefore the crosslinks between the dynamics of the wind and the control strategy of the WTG are considered in the wind load application system. Finally we give an outlook on the 4 MW test bench that will be installed in Aachen in mid of 2014.

Introduction

Growing wind turbine sizes, shorter development times and downtimes due to unforeseen damages of drive train components and rotors result in a decline of WTG availability. To achieve the availability which has to be guaranteed by the system manufacturer (over 97 %) and to reach the target of planned contribution to the energy production, the overall system availability must be increased efficiently. Dynamic loads on wind turbine drive trains caused by wind and grid effects during operation lead to complex vibrations and deformations in the entire drive train. These loads, vibrations and deformations must be taken into account regarding load calculations to get reasonable results. The worldwide demand for system tests of wind turbine nacelles is steadily increasing. Beside the completed and publicly available system test benches in the USA, Spain and Germany, additional test benches are being built up in Denmark, England, USA and Germany. These test benches are used for function tests and for fatigue tests of entire WTG nacelles. Additionally OEMs like Vestas [VEST13] or Areva [AREV13] have recognised the importance of system tests of the drive train or its components for the validation of new developments or components by tier suppli-
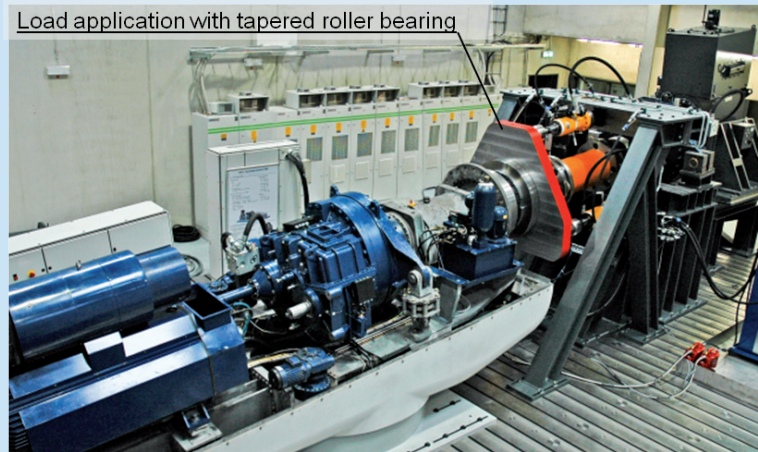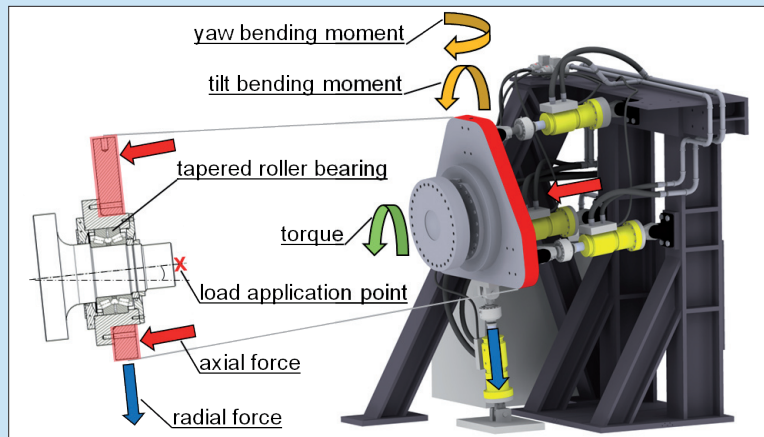
Fig. 1: 1 MW WTG system test bench

Fig. 2: Hydraulic load application system

ers, since this approach can lead to a higher quality and reliability.

The WTG is an active component inside the testing environment. By controlling the pitch- and yaw system as well as the generator speed, the nacelle is able to massively effect the loads on itself. The loads on generator side coming from the crosslink to the grid can be influenced by the nacelles control strategy as well.

A control system for the test bench, as well as a test bench environment is necessary to gain an understanding regarding the interaction between hard- and software, to analyse strain and displacements under realistic loads and to develop test procedures with realistic loads for publicly available test benches. The test bench must enable the integration of the WTG as a "black box" hardware component in a simulated wind and grid environment. This hardware in the loop (HIL) approach is the only way to test WTG under realistic conditions without disclosing the operating strategy (OEM core expertise).

Nacelle Test Bench

For the purpose of testing a WTG under the above discussed conditions a demonstrator test bench has been developed at RWTH Aachen University (Fig. 1). The test specimen is a Vestas V52 with a nominal power of 850 kW. The drivetrain concept of the specimen is a classic separated design containing a main shaft 4-point-suspension with two spherical roller bearings and a main-gearbox with one planetary stage and two spur gear stages. The total ratio of the gearbox is 62 and the electrical energy is generated by a high speed doubly-fed induction generator with a partial converter.

The test bench uses a combination of a high speed motor and a modified WTG gearbox to apply high torques to the WTG rotor shaft. Therefore the load capability of the prime mover attains the nominal input torque of the WTG.

To provide realistic loads at the rotor flange of the nacelle an additional 4 degree of freedom load application system has been developed (Fig. 2). It consists of four servo hydraulic actuators with a nominal force of 160 kN each. Three actuators are arranged parallely to the drive train axis, the fourth actuator perpendicular to the drive train axis. The loads are applied to a triangular structure and passed through a double-row tapered roller bearing on to the rotating shaft.

By different kinds of actuators loads up to 4.5 times of nominal thrust respectly 2.5 of times rotor weight as well as up to 190 kNm of tilt and yaw bending can be performed. These loads are related to the virtual point of load application where all three blade coordinate systems intersect (according to GL). As the rotor hub and the blades are not existent at the test bench this point is located on the middle axis of the shaft flange about 200 mm left of the red marked triangular structure.

The four actuators are employed to apply physical wind
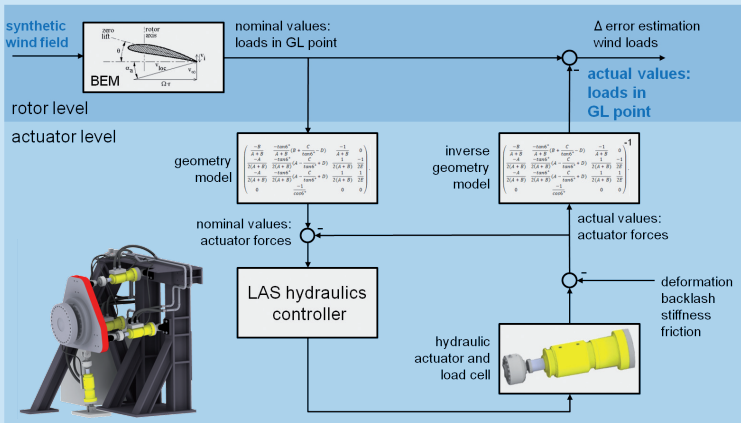
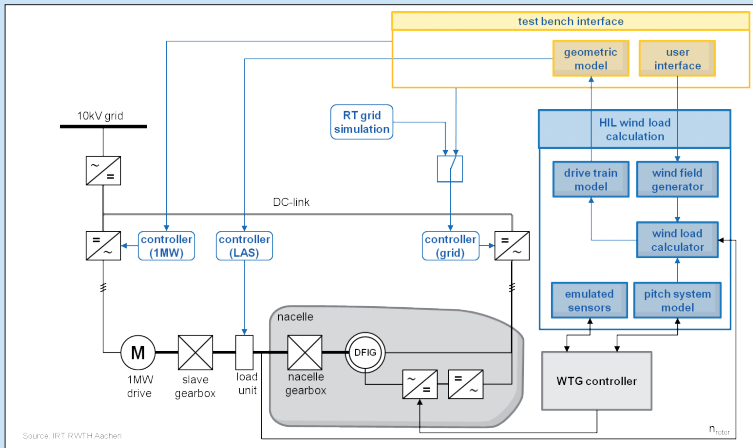Fig. 3:   Control loop of the load application system

Fig. 4:   Hardware in the loop nacelle integration in the test bench

loads on this point. It is necessary to calculate the required forces for each actuator by using a transformation matrix based on a geometric model in order to determine the mutual interaction between them. The forces are controlled on the actuator level (see Fig. 3).

In detail the wind field and force calculation is done at the rotor system level. Therefore a 3D windfield based on the manual input parameters average wind speed, turbulence intesity and oblique-flow is simulated based on the structural and aerodynamic properties of the rotorblades. The mechanical loads at the load application point are calculated using the blade element momentum theory (BET). The loads on rotor level have to be converted by using a geometry model which characterizes the load application system in order to determine the target values for each individual actuator. These target values are fed to the actuator controller which receives the measurement values of the forces from each of the load cells that are paired with the actuators. For reverse calculation of the physical windloads at the load application point out of the actual, measured values of each individual actuator force an inverse geometry model is used. Based on these results an error estimaton of the applied wind loads can be done. The performance of the 1 MW prototype load application system has been tested in an extensive measurement campaign. The measurement campaign was focussed on the overall performance and was based on synthetic load cases using different combinations of static and dynamic forces and

moments. As a result of these measurements it has been identified, that the load application system performs best in operation points with high values of average load and that in most cases dynamical excitations greater than 3 Hz can be applied without violating an error criterion of 2 %, [SCHE12a].

HIL Integration of a Nacelle in a Full Scale Test Bench

Beside the objective to show, that the accuracy of the load application system fits the dynamic requirements for windload application, the 1 MW nacelle test bench focussed on the verification, that a full nacelle can be tested inside a hardware in the loop environment. Fig. 4 gives an overview about the integration of the nacelle into the test bench HIL control system. The system consists of four parts. The HIL wind load calculation, the test bench interface, the mechanical test bench and the nacelle with the WTG controller. The prime mover and the load application system are controlled by the test bench. The target values for the grid-side converter can be provided by the test bench interface as well as for FRT tests by using an independent realtime grid simulation.

Taking a look at the HIL wind load calculation, a signal exchange between the test bench interface, the wind turbine controller and the test bench sensors can be seen. The input data for the wind field generation is transmitted by the user. The state variables of the mechanical system are
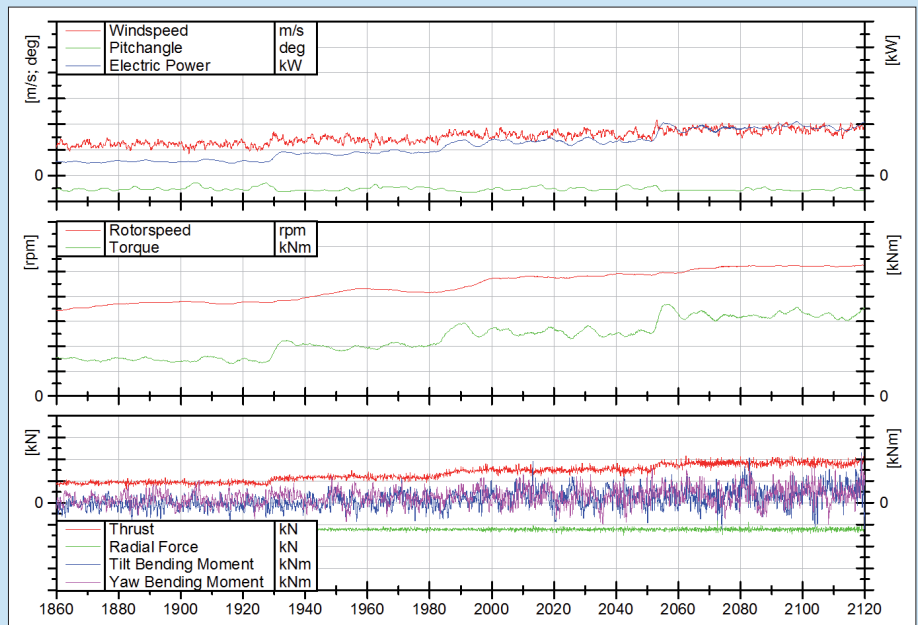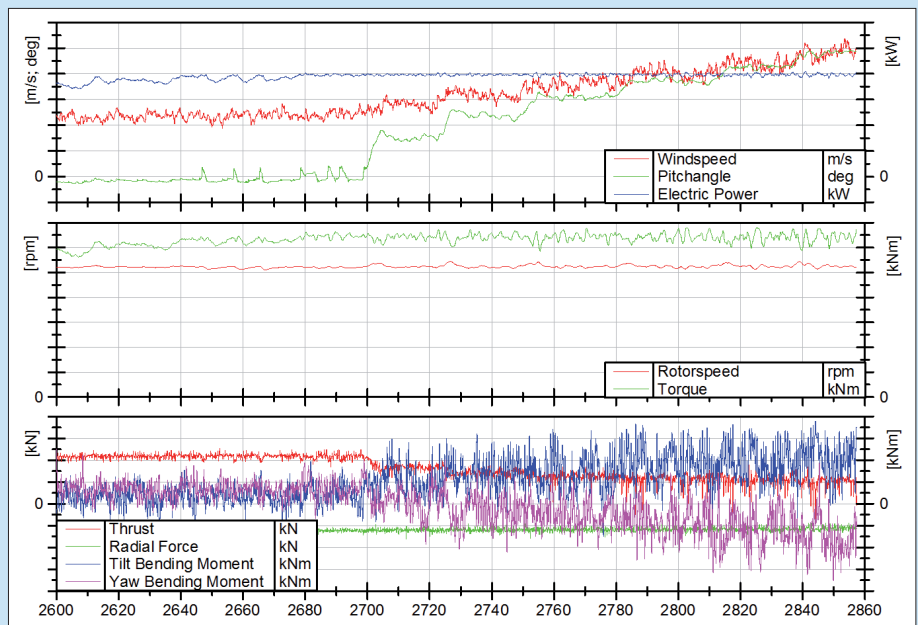
Fig. 5:   HIL operation mode at partial load

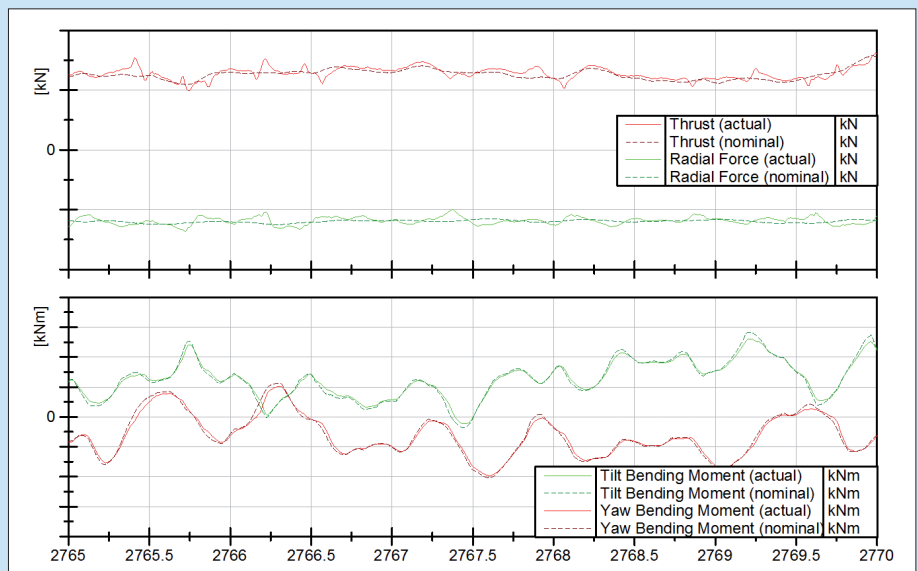Fig. 6:   HIL operation mode at full load

Fig. 7:   Comparison of target- and actual load values
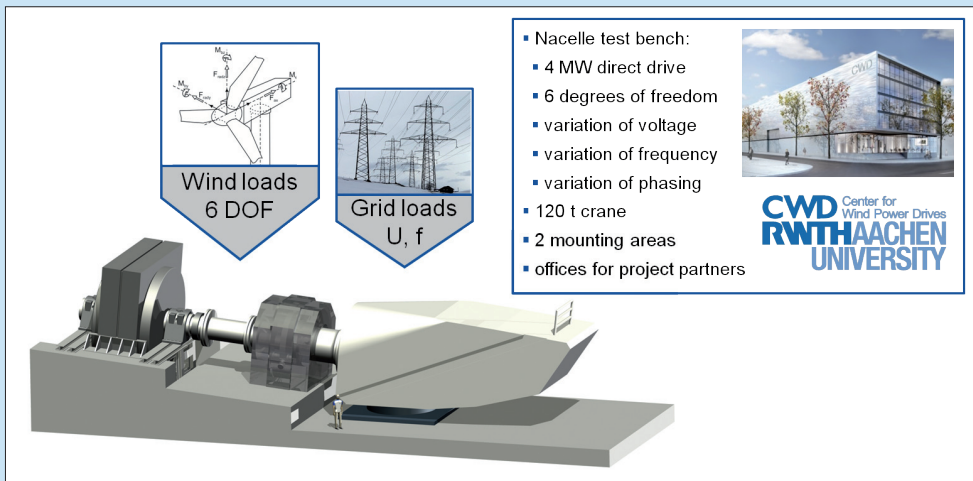
directly read from the test bench sensors to prevent dead times. The target value for the pitch system is generated by the wind turbine controller and processed by a pitch system model to consider load backlash effects on the pitch actuator. The calculated value of the pitch angle is feed back to the nacelle controller to close the control loop and to generate a realistic pitch behaviour. The windloads are calculated and processed by a drive train simulation based on the wind field and the state variables of the wind turbine. The drive train model considers inertia effects between the test bench and the real nacelle in the field. The control of the power converter of the doubly fed induction generator takes place totally unaffected inside the nacelle control system. Missing sensor and status signals are emulated to prevent errors in the nacelle controller. The implementation of all these models and calculation steps are done in rwal time. So ist possible to run the nacelle with its own controller as used in the field.

Test Results from HIL Operation Mode

After the explanation of the HIL system approach the next chapter illustrates an overview of the system test bench under operation, showing the nacelle operating under high and low wind conditions as well as that the load application is capable to fulfil the dynamic requirements of wind load application using the HIL operation mode. While running in the HIL operation mode the input parameters on the rotor side define the wind field in which the nacelle is operating. Fig. 5 shows a time history of a system test using the HIL operation mode. The wind speed, which is superimposed by a turbulence intensity of 16%, starts in the measurement plot near the cut in wind speed and increases gradual. For the whole time history the power controller of the nacelle is running as the nacelle is operating under partial load conditions.

While the pitch angle stays at an optimum value under partial load conditions the power controller of the nacelle sets up optimal operation points by controlling the speed of the generator to get a maximal electrical power output. This effect can be observed at 1930s, 1985s and 2055s while a transient rise of the wind speed results in a temporary overshoot of the torque. By increasing the rotor speed to a higher level the nacelle controller sets up a new operation point with a maximal electrical power production. Taking a look at the wind loads in the third graph it can be observed, that the thrust is strongly affected by the increased wind speed while the tilt bending moment and yaw bending moment are only slightly affected. The radial force which represents the missing rotor weight at the test bench remains at a constant level.

In comparison to Fig. 5, Fig. 6 shows a time history of a system test reaching the maximum load range of the nacelle. At the beginning of the measurement plot the nacelle operates under the generator based power controller as the electrical output power is below the maximum value. In the time between 2648s and 2798s, it can be seen, that the nacelle switches the controlling strategy between power- and pitch-control for multiple times. This becomes noticeable by observing the pitch angle, for the times, where the maximum power production of the nacelle is reached. The variation of the angle of attack results in a degreased aerodynamic torque as well as a dropping electrical power production.

At the time of 1800s the wind speed is increased stepwise, so that up from this point to the end of the time history plot the pitch-controller of the nacelle remains active. Directly with the increased wind speed it can be seen, that the nacelle controller pitched the rotor blades out of the wind significantly, to limit the electrical power production. The average value of the torque is nearly unaffected, as the pitch behavior compensates the torque increase based on the raised wind speed. Significant influence of the pitch behavior can be observed at the other wind loads, shown in the third graph. While the thrust is reduced by the change of the angle of attack, the aerodynamic boundary conditions at the blades result in massively increased absolute tilt- and yaw-bending moments. In previous measurement campaigns the performance of the load application system has been evaluated at the base of synthetic and offline simulated load cases [Sche12b].

By analyzing measurement data of system tests using the HIL operation mode, the overall performance of the load application system is tested again to evaluate whether

the high load dynamic based on turbulent wind conditions as well as the nacelle controlled pitch behavior will be reached. Fig. 7 shows a nominal-actual value comparison of the highly dynamic bending moments for a zoomed time-period of Fig. 6. The accuracy of the load application system is quite good and the signals show only minor deviations. The evaluation of several system tests under different conditions using the HIL operation mode shows, that the dynamic performance of the load application system is adequate to apply realistic dynamic wind loads within the relevant frequency range of 5 Hz. Beside the two operation modes "partial load" and "full load" shown here, the operation modes "grid connection", "fast stop" and "fault right trough FRT" were applicated and have been analyzed in the HIL test bench operation .

Conclusion and Outlook

With the development and the commissioning of the 1 MW demonstrator test bench at RWTH Aachen University the first WTG system test bench in the world has been starting operation, which is capable to run a system test of whole nacelles with original controller. The rotor system is replaced by a Hardware in the Loop model. Based on the results of the measurement campaign on the 1 MW demonstrator, a 4 MW WTG system test bench has been designed. This new improved test bench is located at the Campus of the RWTH Aachen University and will be operated by the Center for Windpower Drives. Start of operation is in September 2014.

The geometry of the 4 MW test bench allows testing of nacelles with a maximal overall length of 18 m and a rotor hub height of 4,5 m. The test bench is driven by a permanent magnetic direct drive manufactured by GE with a nominal output power of 4 MW. By using this kind of input machine it will be possible to apply high torque dynamics as calculated by the real time aerodynamic load simulation or given by field data. Further wind loads will be delivered by a hydraulic Non-Torque-Loading System (NTL) manufactured by MTS. The system is able to stress the drive train with wind loads in five degrees of freedom so the whole test bench can apply wind loads in all six degrees of freedom (Fig. 8). The NTL contains six pairs of pre-stressed actuators which are located on a spinning journal bearing disc and on a radial bushing. By using the hydrostatic journal bearing principle and the pre-stressed actuators the NTL system is free from backlash.

In addition to the application of wind loads this test bench is able to provide loads on the grid side of the nacelle. The grid loads including the special events like voltage drops or FRT tests will be done on grid voltage level of 20 kV. The grid simulation and the power electronics are completely decoupled from the public grid, so it will be possible to perform FRT tests at any time.

In addition to the HIL system for the aerodynamic loads a HIL system for the realtime calculation of grid loads and system perturbation has been developed and tested at the 1 MW demonstrator. Both simulation environments, will be ported to the 4 MW system test bench and integrated into the control system of the test bench to create the most advanced testing facility for on-shore wind turbines.

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