Driving Torque Control for a Nacelle Test Bench

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Abstract. Recently wind industry paid a lot of attention to ground testing facilities in order to improve reliability of wind turbines by undergoing overall system tests at an early stage of development. Some experience has been gained during the last years with drive train test benches, that allow for pure mechanical and electrical tests of the turbine’s components. Since the loads occurring inside a wind turbine significantly depend on its control strategy, the natural extension of drive train test benches are so-called nacelle test benches, which also include the wind turbine’s controller. The worldwide first nacelle test bench was installed and launched at RWTH Aachen University in 2013. This nacelle test bench was set up as a demonstrator and has a rated power of 1 MW.

For the demonstrator test bench a gearbox-based drive train concept, which does not intrinsically meet the high dynamic requirements of the real-time aerodynamics simulation, was chosen. In this paper the mechanical concept is reviewed from a control engineering point of view and a detailed control model is presented and validated using measurement data. In order to minimize the impact this mechanical limitations have and to achieve the dynamics and accuracy required, a driving torque controller is proposed. Due to the communication layout at the nacelle test bench, time delay in data transfer cannot be omitted for controller design.

Experiments confirm that the driving torque controller allows to operate a wind turbine at the nacelle test bench and suppresses unrealistic, test bench-related torque dynamics.

1. Introduction

The installed wind power capacity in Europe constantly increased during the last decade. In 2013 the share of wind energy in the total power generation capacity in Europe was about 13% [1]. Along with the increased installed capacity, the reliability of the electric energy supply depends more and more on the reliability of wind turbines. Their reliability improved during the last years amongst others due to better knowledge about loads. This knowledge was used e.g. for sophisticated hardware-in-the-loop (HIL) component testing [2–4] or as basis for specific test procedures for single components [5]. Nevertheless the failure rate is still somewhat different from zero. Especially failures of drive train components cause long stand still times. In order to further reduce the failure rate of the assembled drive train components, successful HIL-testing at component level has to be expanded towards system level HIL-tests, including all components necessary for energy conversion as well as the control system.

To the authors knowledge only a few publications dealing with test benches for wind turbine drive trains of the multi-MW class are available so far [6–10]. Those present test bench concepts, which are in many aspects similar to the one dealt with in this paper, but focus on the electrical system in their publications. None of them shares experimental data or gives details about the control of the mechanical system components so far. Ultimately only one of those concepts,
the Fraunhofer IWES test bench in Bremerhaven (Germany) [10, 11], allows for full nacelle testing by including the wind turbine controller, as it is possible with the RWTH Aachen University test bench.

In this paper the driving torque control of an 1 MW nacelle test bench is addressed. On one hand the design of such controller has to account for the dynamic requirements given by the aerodynamic properties. On the other hand it has to take into account performance limitations caused by the drive train concept and the given communication topology. The designed controller will be tested and validated in experiments at the nacelle test bench and practical performance limitations will be discussed in detail. The nacelle test bench considered was launched in 2013 and is a demonstrator for a planned 4 MW test bench.

This paper is organized as follows. The next section gives an overview about the 1 MW demonstrator nacelle test bench, its features and communication structure. Thereafter the drive trains of the test bench and the tested wind turbine will be modeled and the chosen drive train concept of the test bench will be discussed. This will be followed by the design of the driving torque controller, which shall compensate for mechanical shortcomings of the chosen concept. Finally experimental results of the wind turbine operating at the nacelle test bench will be presented.

2. Nacelle Test Bench Setup
The 1 MW nacelle test bench and the specimen used for simulations as well as experiments throughout this paper are shown in figure 1. The specimen is a Vestas V52 with a rated power of 850 kW. It consists of a gearbox-based drive train with 26 rpm rated rotational speed with respect to the low speed shaft (lss). As indicated in the picture the load application system can be divided into the non-torque load (NTL) unit, necessary for e.g. thrust force and bending moments, and the motor gearbox combination for the driving torque, with a rated power of 1 MW.

2.1. Emulated Systems
To operate the wind turbine and its controller at the nacelle test bench the

- electrical
- auxiliary and
- mechanical
systems, which the wind turbine is usually surrounded with, need to be emulated in real-time. Those emulated systems are supervised and coordinated by a global test rig control and embed the tested wind turbine in an artificial environment as illustrated in figure 2.

![Diagram](image.png)

**Figure 2.** Simplified schematic of the assembly of the real-time simulations and hardware, which embed the wind turbine at the nacelle test bench.

Wind turbines are generally connected to an electrical grid, which has to be emulated at the test bench. This is done by a real-time grid simulation based on RTDS, which controls an inverter system connected with the wind turbine [12]. The measured current is fed back into the grid simulation to compute its current state. This setup not only allows for grid simulation at normal state, but also at failure states, so that low voltage-ride-through or even fault-ride-through tests can be conducted with this test bench, as presented by Helmedag et.al. [13].

The control system of the wind turbine is reliant on sensors and actuators which are partly not available at the test bench anymore, as for instance the wind vane, pitch and yaw system. Such components are replaced by real-time simulations which provide measurement data and feedback signals to the controller, according to commands caught from such.

For the rotor of the wind turbine is dismounted at the test bench, its influence, which is naturally of highest importance, has to be emulated. This is done by the mechanical system. This consists of of two real-time simulations: an aerodynamic and an inertia simulation. The resulting torques and forces are applied to the specimen via the NTL and the driving motor. The aerodynamic simulation is based on a common BEM-code, extended by corrections, and designed to operate in real time. The measured rotation speed, pitch and yaw angle are input to this simulation. So is an artificial turbulent wind field, computed in real-time, based on user input regarding mean wind speed and turbulence intensity. For this paper focuses on the control of the driving motor, no further details about the simulations and the NTL unit will be given here but can be found in [14, 15].

2.2. Communication Structure and Simulation Hardware

The demonstrator test bench was installed at a multi-purpose test bed at the Heavy Drive Train Center Aachen, which provided the driving motor. The existing global test rig control was only slightly extended to interface the three emulation systems mentioned before, while the communication concept concerning the driving motor was not modified. For this reason the communication of reference and measurement data between the simulation hardware and the motor is not as straightforward as figure 2 suggests.
As shown in figure 3 the control algorithm for the driving torque, the aerodynamic and the inertia simulation (mechanical software) as well as the sensor-actuator simulation (auxiliary system) are implemented on the same rapid control prototyping (RCP) hardware [16], a dSpace Autobox equipped with the DS1006 processor board [17]. The implementation of the mechanical software and the auxiliary system on the same hardware allows for high speed exchange of model output data e.g. pitch or yaw angle from auxiliary system to the aerodynamic simulation. In contrast, the reference and measurement data of the driving torque (denoted as $T_{ref}$ and $T_m$ in figure 3) are piped through the global test rig controller, which is connected to the motor and the RCP hardware via two separate CAN-buses.

Due to the sample time of 0.01 s the communication tasks in the global test rig controller and the RCP hardware are executed with, information on both buses are exchanged at a sampling rate of 100 Hz. Hence the data transfer from the sender to the receiver can be delayed by up to two half of the task’s sample time. This holds for the reference as well as the measurement data transfer, so that the whole control loop has a time delay of up to 20 ms.

![Figure 3. Communication architecture regarding the reference and measurement data of the driving motor.](image)

**Figure 4.** Assumption for modeling the drive trains of the test bench, the specimen and their coupling.

3. Test Bench Model
In this section a model of the nacelle test bench considering only the rotational degree of freedom is presented, which can be used for simulation and controller design of the driving motor.
3.1. Model Structure
As shown in figure 1 the demonstrator nacelle test bench is set up as a back-to-back gearbox configuration. One belongs to the specimen and one to the test bench itself. Since the motor, the generator and the two gearboxes hold the main share in the inertia of the overall drive train they are modeled as four lumped masses \( J_1 \ldots J_4 \) connected via spring and damper systems as shown in figure 4. Thereby the motor torque \( T^* \) and the generator torque \( T_G \) act as inputs to this mechanical system, which can be described as follows:

\[
\begin{align*}
J_1 \ddot{\phi}_1 &= T^* - d_1 (\dot{\phi}_1 - \dot{\phi}_2) - c_1 (\phi_1 - \phi_2) \\
J_2 \ddot{\phi}_2 &= d_1 (\dot{\phi}_1 - \dot{\phi}_2) + c_1 (\phi_1 - \phi_2) - d_2 (\dot{\phi}_2 - \dot{\phi}_3) - c_2 (\phi_2 - \phi_3) \\
J_3 \ddot{\phi}_3 &= d_2 (\dot{\phi}_2 - \dot{\phi}_3) + c_2 (\phi_2 - \phi_3) - d_3 (\dot{\phi}_3 - \dot{\phi}_4) - c_3 (\phi_3 - \phi_4) \\
J_4 \ddot{\phi}_4 &= d_3 (\dot{\phi}_3 - \dot{\phi}_4) + c_3 (\phi_3 - \phi_4) - T_G
\end{align*}
\]

Where \( d_i \) and \( c_i \) denote damping and stiffness constants of each spring and the inertias \( J_i \) the motor, \( J_2 \) the slave gearbox, NTL unit and the coupling, \( J_3 \) the flange, shaft and gearbox of the wind turbine and \( J_4 \) its generator. The assumption that the dynamic behavior of the mechanical system can be described with those linear differential equations is a simplification, since stick-slip effect and speed-dependent friction are present in measurement data. Nonetheless it is assumed that in typical operating points stick-slip effects are negligible and speed-dependent friction is nearly constant. Furthermore the desired model shall be analyzed with classic linear control theory.

3.2. Model Identification
The drive train inertias \( J_1 \ldots J_4 \) are calculated using material and geometrical data of the components, while damping and stiffness coefficients of the springs have to be identified by experiments. Therefore the angular velocity \( \dot{\phi}_2 \) and the torque \( T_{s2} \) were recorded for the input torque \( T^* \) being a step. The stiffness and damping parameters were estimated by minimizing the summed squared error of the measurement and simulation output for \( \dot{\phi}_2 \) and torque \( T_{s2} \).

Figure 5 shows the measured torque \( T_{s2} \) (top plot) and rotation speed \( \dot{\phi}_2 \) (bottom plot) of the identification experiment. The measured torque shows clearly, that the overall drive train of the test bench is extremely flexible and only lightly damped, which is mainly caused by the back-to-back gearbox configuration. Since the generator torque \( T_G \) is set to zero, one end of the drive train is loose, so that the reference torque cannot be tracked accurately. This is especially true since no reference control is activated. Furthermore with the generator torque being set to zero, the rotation speed reaches no stationary value.

The measurement data shown in figure 5, have been used to identify the parameters of the drive train model. The comparison of both, measurement and simulation data is also plotted in figure 5. The torque \( T^* \) as well as the rotation speed \( \dot{\phi}_2 \) show good agreement with the experimental data concerning the main dynamic. As expected, some effects are not fully covered by the linear model. The damping of the torque signal matches well until 3 sec, where the damping changes and an almost undamped oscillation evolves. The already mentioned stick-slip effect can be observed when the drive train starts moving. When the influence of the stick-slip effect is over, the drive train at first behaves extremely similar to a linear spring damper system. To identify the system as such, regardless the stick-slip effect, the input signal \( T^* \) is simply delayed, which can naturally be seen in the simulation results in figure 5.

The model identified with the experimental data shown in figure 5 is now validated with a different set of data which is shown in figure 6. In the validation experiment the torque step was \( 10^4 \) Nm instead of 7000 Nm as for identification. Although the difference of the stationary torque is slightly higher than with identification data, the validation indicates that the dynamic behavior does still match very well. As with the identified data, a harmonic oscillation evolves...
again after a few seconds, probably because of time varying damping coefficients.
Although not all effects are covered by the model, its accuracy is considered as sufficient enough for controller design, since the dynamic behavior is of most importance for active damping control.

4. Torque Control
In this section the driving torque controller is presented. Therefore dynamic requirements of the control loop are formulated before a baseline control scheme is proposed and results are discussed.

4.1. Requirements and Limitations
The main task of the torque control loop is to damp the torsional oscillation of the drive train in order to allow for steady operation. The second aim is to achieve the maximal possible performance to allow for highly dynamic load application at the flange of the wind turbine.

The minimal desired dynamic is to reproduce the tower shadow’s impact on the driving torque (see figure 7), which corresponds with the 3-P frequency. For the Vestas V52 this is 1.3 Hz at rated speed. As the blades are considered as flexible in the simulations, the reference torque also contains dynamics fairly above the 3-P frequency (see figure 8) which are not further considered throughout this paper, but will be in future controller designs.

The main existing limitation for the control is the sample-time related time delay which was introduced and explained in detail in subsection 2.2.
4.2. Controller Design

The main focus of the driving torque controller is to damp the eigenfrequency of the test bench’s drive train. At the same time the dynamics of the reference torque $T_{\text{sim}}$, given by the simulations, shall not be affected. For this reason not a reference control is chosen here, but a disturbance rejection control as figure 9 shows. The sample-time-related time delay (see subsection subsection 2.2) is represented by $T_T$. The controller $C(s)$ is chosen as simple as:

$$C(s) = \frac{K_d \cdot s}{T_F \cdot s + 1}$$

(5)

Due to the measurement sampling frequency of 100Hz the filter frequency $1/T_F$ of $C(s)$ is chosen to 40 Hz. Considering the Nyquist criteria for stable open loops [18], the bode plot of the plant with time delay in figure 10 indicates that a proportional feedback above one results in an unstable closed loop due to the rapid phase drop caused by the time delay. For the given control
law \( C(s) \) the phase is increased by 90° for low frequencies which allows to increase the gain with respect to stability margins. The open loop of a possible implementation is also shown in figure 10. The bode plot of the corresponding closed loop from reference torque \( T_{\text{sim}} \), given by aerodynamic and inertia simulations, to the applied torque \( T_{s2} \) at the specimen is plotted in red. It shows, that the resonance frequency can be damped significantly and the sensitivity can be slightly increased at higher frequencies.

4.3. Simulation Results
The stability issues mentioned before are mainly sample-time related and caused by the suboptimal communication topology at the demonstrator test bench. To illustrate the influence of the time delay, the same controller and test bench model is simulated with and without time delay. The step responses for both scenarios are shown in figure 11. Compared to the uncontrolled step response, both controlled step responses reduce the settling time of the torque significantly. Compared with each other, the results indicate, that even if control parameters are not tuned for the time-delay-free case, better performance can be achieved thereby. For the realistic case with activated time delay, the minimal dynamic requirement defined in subsection 4.1, the 3-P frequency of the specimen of 1.3 Hz, seems to be hardly met when the generator torque is set to zero. Fortunately experimental data of the fully functioning test bench (not included in this paper) show, that during operation \((T_G \neq 0)\) the tower shadow effect is reproduced nicely.

![Figure 11](image1.png)  
**Figure 11.** Comparison of simulation results for controlled step responses with and without time delay \( T_T \).

![Figure 12](image2.png)  
**Figure 12.** Experimental results for controlled step responses.

5. Experimental Results
In this section the designed controller is investigated experimentally. Thereby two different scenarios are considered. For comparison with the simulation results of the former section, the step test is repeated in experiment with activated torque control. Additionally the dynamic behavior of the drive train during start-up phase of the wind turbine at the test bench is compared for activated and deactivated driving torque controller.

5.1. Step Response
The experimental results are plotted in figure 12 and show that with activated driving torque controller, the overshoot and the settling time of the torque can be reduced significantly, compared to the uncontrolled case. Undeniable, the experimental results do not meet
expectations raised by simulation results. The exact reason for the difference of simulation and experiment is not yet clear. Non-linear effects can surely be a reason, especially since the critical gain for stability was found to be equal in experiment and simulation.

5.2. Operation

Although the experimental results for the step test are not as good as expected, the designed controller does still improve the dynamic behavior of the test bench significantly. For confirmation a short sequence of the start-up phase of the wind turbine operated at the nacelle test bench is used.

The figures 13 and 14 show the pitch angle desired by the wind turbine controller, the measured torque and the measured rotation speed during wind turbine start-up, with activated (figure 14) and deactivated (figure 13) torque controller. Since the controller also influences the rotational speed, the control actions taken by the wind turbine are not perfectly the same in both experiments. The wind speed is set to cut-in wind speed of 4.5 $m/s$ without any turbulence. The only measurement data available with deactivated torque control was derived at an early stage of the test bench launch. Therefore not the final version of the aerodynamics simulation was used during these experiments, so that e.g. the tower shadow’s impact is not simulated.

The plots show the acceleration of the wind turbine, before the generator is connected to the grid at approximately 22s and 23s respectively. For the uncontrolled case, not only the gearbox tooth play causes drive train oscillations, but also connecting the generator to the grid triggers an oscillation clearly to be seen in the measurement in figure 13. When the driving torque controller is activated in figure 14, the generator connect procedure still causes this oscillation of the drive train. But after only two periods it is perfectly suppressed, which is excellent concerning realistic testing of wind turbines for instance during start-up phase.

6. Conclusion and Outlook

This paper gives an overview of the torque control of the driving motor at a demonstrator nacelle test bench. A control model of the test bench’s drive train was presented and validated
using experimental data. A baseline driving torque controller for active damping of drive train oscillations was developed. Simulation and experimental results confirm that despite an extremely flexible drive train and a handicap in the given communication topology, the controller allows for dynamic torque application in the range of the 3-P frequency and furthermore significantly damps undesired oscillations extremely well. Although, for the sake of comparability only early results of the nacelle test bench operation were shown the controller proved to enable wind turbine operation in this artificial environment.

Looking at the 4 MW nacelle test bench currently constructed, where a direct drive motor will be used and the shaft of the drive train will be stiffened, higher torque dynamics will be achievable so that the influence of the simulated flexible blades is reproduced adequately. Furthermore the communication topology will be optimized for minimal time delay to guarantee optimal prerequisite for high dynamic load application and control.

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References

[1] EWEA T 2014 Wind in power: 2013 European statistics brussels, Belgium
[2] Shan M, Duckwitz D, Fischer B and Brosche P 2012 HiL-Simulation Platform for the Test of Wind Turbine Controllers 11th German Wind Energy Conference (DEWEK)
[3] Caselitz P, Geyler M, Giebhardt J and Panahandeh B 2006 Hardware-in-the-Loop Development and Testing of New Pitch Control Algorithms Proc. European Wind Energy Conference
[4] Gauterin E, Harborth N, Pieniak N and Twele J 2012 PHIL Pitch Systems in the Hardware-in-the-Loop-Test 11th German Wind Energy Conference (DEWEK)
[5] Holierhoek J G, Lekou D J, Heequet T, Sker H, Ehlers B, Savenije F J, Engels W P, van de Pieterman R P, Ristow M, Kochmann M, Smolders K and Peeters J 2013 Wind Energy 16 827–843
[6] Li H, Steurer M, Shi K, Woodruff S and Zhang D 2006 IEEE Transactions on Industrial Electronics 53 1144–1150
[7] Saniter C and Janning J 2008 IEEE Transactions on Power Electronics 23 1707–1715
[8] Fox J C 2013 The Clemson University Grid Simulator Proc. 1st International Workshop on Grid Simulator Testing of Wind Turbine Drivetrains (NREL)
[9] Neumann A 2013 An Introduction to the Narec Grid Emulator Proc. 1st International Workshop on Grid Simulator Testing of Wind Turbine Drivetrains (NREL)
[10] Jensch T 2013 LV/RT Testing on DyNaLab Electrical certification of Windturbines on Test Benches? Proc. 1st International Workshop on Grid Simulator Testing of Wind Turbine Drivetrains (NREL)
[11] Fraunhofer IWES 2013 Teststand der Superlative: Dynamic Nacelle Testing Laboratory DyNaLab online
[12] Helmedag A, Isermann T, Monti A, Averous N, Stieneke M and De Doncker R 2013 Multi-physics power hardware in the loop test bench for on-shore wind turbine nacelles ECCE Asia Downunder (ECCE Asia), 2013 IEEE pp 221–226
[13] Helmedag A, Isermann T and Monti A 2013 Fault ride through certification of wind turbines based on a power hardware in the loop setup Applied Measurements for Power Systems (AMPS), 2013 IEEE International Workshop on pp 150–155
[14] Schelenz R, Bosse D, Radner D and Jacobs G 2012 Demands on Dynamics of LAS (Load Application System) for Full Scale Ground Testing of 1 MW Wind Turbines 11th German Wind Energy Conference (DEWEK)
[15] Bosse D, Barenhorst F, Radner D and Schelenz R 2013 Analysis and Application of IEC61400 Orientated Wind Loads for Full Scale Ground Testing Proc. of the Conference for Wind Power Drives pp 103–123
[16] Abel D and Bollig A 2006 Rapid Control Prototyping - Methoden und Anwendungen (Springer)
[17] DS1006 Processor Board URL http://www.dspace.com/
[18] Lunze J 2010 Regelungsstechnik I (Springer-Verlag Berlin)