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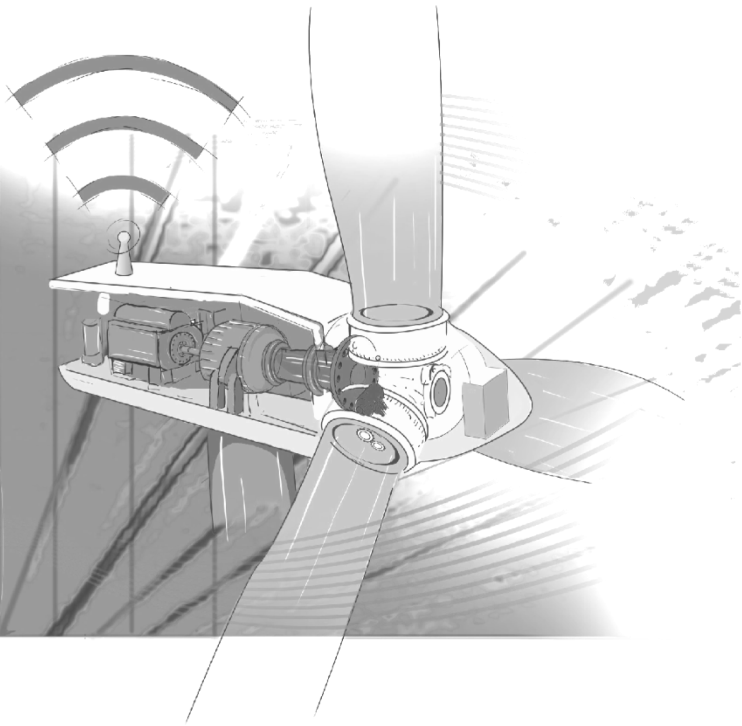

BOOK OF ABSTRACTS

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Gearbox Bearings I

A new Generation of Hydrodynamic Plain Bearings, enabling the next Step in Gearbox Torque Density

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Abstract: The wind industry is facing a continuous pressure to reduce the Levelized Cost of Energy (LCoE), resulting in new drivetrain designs. Increasing gearbox torque density is hereby required to limit the weight up-tower and to limit the size of the largest components for transportation. To achieve higher torque density, especially the first planetary gear stage has been changed in modern wind gearboxes to a multi-planet system. This system has a high number of planet gears of relatively small gear diameter resulting in limited space for the bearing supporting the planet gears. This has resulted in the implementation of hydrodynamic plain bearings (HPB) in new multi-MW gearbox designs, replacing roller bearings because of the smaller cross section.

The most common HPB solution applied today in wind gearboxes is a mono-material bushing, which can be mounted fixed to the planet pin, the planet gear or as a floating bushing between pin and gear wheel.

This presentation will focus on a next generation of HPB, based on a specifically designed sliding material sprayed directly on the planetary pin. Due to the smaller cross section, this cost-efficient solution will enable a next step in downsizing of the planetary gear and hereby increase the gearbox torque density even further. Moreover, this versatile technology allows the use of different materials depending on the application requirements.

The next generation HPB is being tested on a down scaled planetary gear test rig at different wind turbine gearbox operating conditions, including the typical tough conditions for HPB such as mixed lubrication conditions, dynamic excitation, load/speed changes, low speed and high loads seen at single blade assembly conditions, as well as high speeds and high loads seen during overload conditions. Simultaneously comprehensive simulation campaigns have been performed to evaluate and optimize the designs of the downscaled and full-scale HPBs.

Validation of Plain Bearings on Planetary Stages for Single Blade Installation

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Abstract: Plain bearings used in a wind turbine gearbox are exposed to challenging operating conditions during single installation of the turbine blades. This paper describes the resulting loads on component level derived by means of analysis and shows how the ZF Wind Power plain bearing solution for planet bearings has been successfully validated on component, sub-system and system level.

Evaluation of wear models for the wear calculation of journal bearings for planetary gears in wind turbines

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Abstract: To increase the power density of the electromechanical drive train of wind turbines, journal bearings can be used as planetary gear bearings instead of rolling bearings. This technological change presents new challenges. For example, wind turbine drive systems are subject to dynamic and low-speed operating conditions which can lead to an accelerated abrasive wear of the journal bearings. In addition, oil supply failure or peak loads due to wind gusts and grid and power converter faults could potentially result in catastrophic failure due to adhesive wear in a very short time. Such operating characteristics are, therefore, critical regarding the journal bearing wear lifetime and must be considered in the design. The successful implementation of journal bearings in wind turbines depends on a reliable estimation of adhesive and abrasive wear. In this paper, five different models for the wear calculation of journal bearings are evaluated regarding their suitability of wear calculation of planetary gear bearings in wind turbines. For this purpose, the following evaluation criteria were defined: parameter uncertainty, parametrization effort, in particular number of parameters, parameterization method and load case dependency of parameters and calculation effort. In order to be able to evaluate the wear models, the wear models are numerically implemented and the wear of a test journal bearing is exemplarily calculated under load conditions, which are comparable to load conditions in a wind turbine. Relevant influences from the wind turbine system such as lubricant, material and manufacturing dependent surface influences like roughness and hardness are considered. The wear models are evaluated with respect to their fulfillment of the defined criteria. The resulting evaluation allows the selection of a wear model that can be used to calculate the wear of planetary gear journal bearings in wind turbines, considering the available input variables.

Gearbox Bearings II

Journal Bearings in Bind Turbine Gear Units – Performance - Extended Robustness and Load Density – Future aspects

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Abstract: Journal bearings in wind applications is getting more famous. The application planetary wheel bearings are entering the business since several years. Looking into the future robustness and load density for journal bearing applications in this business seams to the next important driver. To ensure ongoing of the successful story up to now, future aspects will be discussed.

Overload situations, wear behavior and emergency stops were in focus in the past, today the main focus are special modes like non-operational modes, no grid modes, e.g. single blade installation and reduced noise mode operation with impact to the journal bearings will become more important within the worldwide climate goals.

The experiences have been enlarged in the last four years with different types of JB-gearboxes performing in turbines.

The presentation provides an enlarged insight of the new challenges upcoming in the near future in regard to higher load densities and more robustness as key performances of journal bearings in wind turbine gear units.

Key wording: SBI-, no oil-, mixed friction operation

Designing and Qualification of Journal Bearings for Planetary Gears in Wind Turbine Gearboxes

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Abstract: The conventional planetary gearboxes of wind turbines usually utilize roller element bearings as supporting elements for the planetary gears. Compared to a roller element bearing, a sliding bearing has fewer components and requires less space to carry the same load. Therefore, in large power gearboxes there is a pressing need to apply sliding bearings to improve power density. In an industrial journal bearing, the unit pressure is typically less than 6.2 MPa, and the preferred minimum oil film thickness is ~25 µm. However, in a wind turbine gearbox the unit pressure in a journal bearing of a planet gear can easily reach 15 MPa, which leads to a minimum film thickness of 3 µm to 5 µm. In some heavy load and low speed conditions, the bearing even operates in a mixed lubrication condition, and structural deformation is not negligible when predicting the performance of such fluid film bearings.

A sliding bearing usually features a soft material on the stationary bore to protect the shaft when a direct contact between the stator and spinning shaft occurs. However, in wind turbine gearboxes the bearing material is on the surface of the planetary pin. In such a situation, centrifugal casting method to apply tribology material on the pin surface is no longer applicable as centrifugal casting can only apply material onto an inner bore. One of the methods to put a bearing material on the pin is to install a sleeve on its outer diameter. The sleeve may be casted from copper alloy. A more favorable method to further reduce cost is to directly apply the tribology copper alloy layer on the pin surface. This paper presents the process on the designing and qualification of a journal bearing with copper alloy directly applied on the outer surface of a pin using laser additive manufacturing method. Since the cladding layer is only about 1 mm to 2 mm in thickness, the cost can be reduced greatly compared to the thick copper sleeve solution without compromising the performance of the bearing.

Simulation methodology for the identification of wear-critical operating conditions of plain bearings in wind turbines

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Abstract: The usage of journal bearings as planetary bearings in wind turbines instead of roller bearings has become more common in recent years. Their usage is advantageous, due to smaller installation space needed compared to roller bearings allowing for higher power densities of wind turbine drive trains. However, this technology presents a challenge since there is currently no standardized approach for the design of planetary journal bearings regarding wear. Due to varying wind speeds and dynamic operating events a large variation of loads has to be considered in the design process of a planetary journal bearing for wind turbines. Some of these loads are considered potentially critical to the journal bearing in terms of wear. Identifying these critical load areas early in the design phase supports a reliable bearing design and wind turbine operation. This paper introduces a method to identify critical operating conditions for planetary journal bearings using a simulation tool chain, which couples a multi body simulation (MBS) model of a wind turbine with an elasto-hydrodynamic (EHD) model of the planetary journal bearing. Based on the EHD results critical operating conditions are determined for the planetary bearing. Furthermore, methods are implemented to reduce the number of required EHD simulations for analysing the bearing design. The combination of the identification of critical operating conditions, while reducing the computational effort leads to a simulation methodology, which enables a faster bearing design assessment considering the wide variation of wind turbine operating conditions. The applicability of this method is demonstrated by a simplified use case. Firstly, this paper introduces the MBS model and the parameter space that describes possible combinations of bearing loads such as forces, moments and rotational speed. Due to the number of combinations and the EHD computing effort, the identified parameter space is secondly sampled statistically to reduce the simulation effort. A risk map is derived from the EHD results, to easily indicate potentially critical operating conditions for the planetary journal bearing.

Efficient Elastohydrodynamic Gearbox Simulations

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Abstract: In current gear box designs of wind turbines roller bearings are mostly used to carry the planet gears. But practical experiences of a world-wide growing numbers of wind turbine show that bearing damages as well as maintenance and service works appear more often than expected, leading to additional costs especially for offshore plants. In consequence, alternative gear box designs with hydrodynamic bearings are developed, aiming on smaller design space, higher torque density and lower costs for maintenance and service. For gear box systems with hydrodynamic bearings completely different design guidelines have to be developed. Thus, a high-performing and efficient software simulation tool is needed to analyze hydrodynamic bearing concepts for planet gears in an early design stage to understand the system behavior and to reduce cost expensive test benches and prototyping. To reach a highly efficient modelling only a carrier segment with one gear under cyclic symmetry boundary conditions is considered.

As a gear box system can be highly loaded at low speed, wear simulations have to be carried-out to appraise the run-in process. The simulation algorithm considers the change of surface wear contour as well as the change of surface roughness in the area of mixed lubrication.

As an extension to a simulation model with only the planet gear, a model including the sun and ring wheel is presented, providing the teeth forces and moments as a simulation result instead of defining them as boundary condition.

Gearbox Testing and Validation

A revised international standard for gearboxes in wind turbine systems

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Abstract: Gearbox and wind turbine design and application standards have contributed significantly to improvements in reliability over the past two decades. The International Electrotechnical Commission (IEC) 61400-4 standard of wind turbine gearbox design is currently being revised by a joint working group (JWG) of experts in IEC TC 88 (wind energy) and International Organization for Standardization (ISO) TC60 (gears) to further that effort. Experts from ISO TC4 (rolling bearings) and ISO TC28 (lubricants) have actively participated. This revision has implemented lessons learned from industry use of edition 1 since its publication in 2012.

The main document, IEC 61400-4, was pared down to essential design requirements and application-specific recommendations along with a design verification framework. The JWG leveraged concurrent development of other standards, such as IEC 61400-8 on wind turbine structures, to replace edition 1 content. These are described along with how this works with the IEC Renewable Energy certification scheme for wind turbines (IECRE-WE).

The JWG recognized the interest in maintaining informative parts of edition 1 including annexes on wind turbine architecture and loads, bearing and gear arrangements, bearing selection, lubrication system descriptions and lubricant performance recommendations. This information was retained in two technical reports: IEC/TR 61400-4-2 Lubrication and IEC/TR 61400-4-3 Explanatory Notes. Additionally, a technical specification, IEC/TS 61400-4-1, was drafted to provide a reliability calculation method for comparing different design options or conditions. Salient elements of these documents are described.

All four documents were recently distributed for IEC/ISO review, ballot, and comment. Publication is expected in 2023.

Validation of a wind turbine gearbox strain simulation model in service to virtual sensing

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Abstract: Over the last decades, the use of wind power as a source of renewable power has increased, while the Levelized Cost

of Electricity (LCoE) of wind power has fallen. In order to further drive down the LCoE, there is an increasing interest to monitor key turbine quantities in order to improve maintenance procedures and decrease downtime. In this paper, we focus on the indirect detection of one such key quantity, the torque load on the gearbox. In order to avoid expensive direct torque sensors, we study the potential of strain gauges installed on the gearbox housing as virtual torque sensors. Our results verify that the strain response is repeatable, torque-driven and predictable; which are the most important conditions for using the sensors in virtual load sensing. Next, we compare the measured strain response to simulated strain results obtained from a physics-based model. The model consists of a static FE model of the gearbox housing and a torsional model of the shafts and gears in the drivetrain. An optimisation approach selects the FE model node where the simulated strain best matches the measured strain. We conclude that the studied strain gauges are promising for model-based virtual sensing of the torque on the gearbox.

WZL-Double Pulsator - Analogy Test Rig for the Generation of Tooth Flank Fractures at Large Gears

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Abstract: As a result of the enhanced of load-carrying capacity with regard to pitting and tooth root breakage, generation of tooth flank fractures became more frequent. This type of damage differs from existing fatigue damages on the tooth flank in that crack initiation takes place below the case hardened surface layer and the tooth breaks in the area of the active tooth flank. An isolated investigation of tooth flank fractures is currently not possible because there is no analogy test rig available that can reproduce both, the compressive stress due to Hertzian contact flattening as well as the tensile stress due to tooth bending. For this reason, a test rig concept is being developed, manufactured and put into operation in the DFG research project "Analogy test rig for tooth flank fractures", which allows the generation of tooth flank fractures in absence of other damage types. This report deals with the commissioning of the WZL-Double Pulsator as well as first test results. The FE model of the analogy test rig is validated by measuring tooth root strains with strain gauges and comparing them with the calculated strains. Finally, the commissioning is carried out and first tests are performed.

Full-scale fatigue testing of a cast-iron wind turbine rotor shaft

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Abstract: Spheroidal graphite cast iron (EN-GJS), which provides a high degree of design flexibility and the possibility for lightweight design, has benefits as a material for use in structural parts in wind turbines. Comparing components made using the sand casting technique to those made using the chill casting process reveals significant potential to boost strength. However, at present, there is neither a proven design guideline nor reliable material input data for a lightweight component based on this material and fabrication process. This publication presents the results from the Gusswelleproject in chronological order. It starts with the explanation of the final setup and test plan for the full-scale rotor shaft fatigue experiment. The elaborated sensor and operational concept are then presented together with an adequate finite element method (FEM) model of the specimen and relevant neighboring components. The validation of this FEM model to ensure that the loading and the resulting local strains representing the real test bench situation is described. The usage of non-destructive testing to document the condition of the specimen from initial crack formation until integrity loss is explained followed by a comparison between the component fatigue test results and the material-based life-time forecast. A strength increase for chill-cast large components in the range of 50% is indicated. Simulation-based crack propagation studies are performed to qualitatively verify the loads responsible for the observed cracks of the component test and to further develop the possible method for crack predictions.

NVH/Tonality I

Analysing the Influence of Non-Torque Loads on the Excitation Behaviour of Integrated

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Abstract: The Noise-Vibration-Harshness behaviour, especially the tonality of wind turbines, is an important criterion for getting an operating permit of the wind turbine and receiving the acceptance by customers. The tonality behaviour of a wind turbine is mainly driven by the dynamic behaviour of the powertrain and partially by the excitation behaviour of the gearbox. The excitation behaviour of planetary gear stages can be described by the parameter and path excitation and depends on the phase shift based on the macro geometrical parameters. The path excitation is caused by the designed micro geometry but also based on all deviations from the ideal involute. This can be caused due to mesh misalignments by load dependent deflections inside the gearbox. These deflections can be induced by the distortion of planet carriers. In addition, the powertrain integration increases the risk of load dependent mesh misalignments caused by non-torque loads on the gear stages. A robust design must compensate all these deflections. For deriving a robust design under these conditions, the knowledge about the effects must be applied and reflected in the analyse and design methods for gearboxes. This paper will treat the investigations of the influence of non-torque loads on the excitation behaviour of gearboxes. The paper will describe the basics of gear excitations in the context of the powertrain architecture. Furthermore, it will show how the test procedure has been designed to evaluate the excitation behaviour under the influence of non-torque loads behaves. It will conclude with the discussion of the test results.

Model Parameterization and Validation of Electromagnetically Excited Structure-Borne Sound in Direct Drive Wind Turbines

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Abstract: In this paper the methodology and results of the validation of a multi-physical system model of a direct drive wind turbine are presented. The analyzed model serves the purpose of examining the structure borne sound resulting from electromagnetic excitations inside the turbine's generator. To study the accuracy of this model and to increase the confidence in the simulation results, an experimental validation is performed in the course of this work. Hereby, the simulation results are compared with data from a measurement campaign in which the real generator was tested on a full-scale system test bench. The validation takes the structure-borne sound transfer, modal behavior of the generator and effects of structural dynamics into account.

On Optimizing the NVH Behaviour of WTG Powertrains through Technology Transfer across Industries

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Abstract: In geared Wind Turbines, vibrations are driven by gear mesh excitations from the various gear stages, which might lead to resonances. To avoid excessive vibrations and noise, it is crucial to control the NVH characteristics during the product development, e.g. through tailoring the Wind Turbine transfer path.

Various Wind Turbine types do show some typical "global" eigenmodes. Some of these modes are dominated by the stiffness of the output sun shaft of the 2nd planetary stage of the main gearbox. As this shaft typically is long and slender, it forms one of the torsionally softest elements in the Powertrain. As the respective eigenmodes are susceptible to gear mesh excitations, its frequency needs to be carefully adjusted by tuning the respective torsional stiffness of the sun shaft.

Usually, the sun shaft inner and outer diameter as well as the length are limited by the available installation space. Made from steel, there consequently is an upper and lower limit for the torsional stiffness … unless one changes the material.

This paper describes how the limits for the sun shaft torsional stiffness can be pushed by using carbon fiber reinforced plastics (CFRP). For a long time, carbon fibre shafts have been used in other applications like aerospace, automotive and marine. Based on existing know-how from these industries, the design considerations, manufacturing challenges as well as the validation process on component, system and turbine level will be explained.

NVH/Tonality II

Evaluation of a low speed stage coupling with regard to structure-borne sound propagation in a wind turbine

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Abstract: Due to recent advances in the field of broadband aerodynamic noise, tonalities of wind turbines (WT) are increasingly coming into focus in the wind industry. In this case, the structure is excited inside the drivetrain and the structure-borne sound propagates through the machinery and ultimately to the surfaces of the WT, where it is radiated into the ambient air. Since any tonalities are a system characteristic, they should be considered at an early stage of product development. On the one hand, great efforts are being made to develop ever lower-toned drivetrains. On the other hand, tonalities can efficiently be neutralised by systematically decoupling the excitations in the drivetrain from the sound-emitting surfaces of the wind turbine. In addition to the well-studied behaviour regarding the decoupling of non-torque rotor loads from the drivetrain, in this paper the influence of a low speed stage (LSS) coupling on the structure-borne sound propagation inside of an integrated drivetrain is investigated. In a previous study at the Center for Wind Power Drives, it could be shown that in an integrated drivetrain, the transfer paths through the main shaft and subsequently the main bearing becomes the dominant transfer path. This is in contrast to classic bearing configurations where the torque arms of the gearbox are the dominant transfer paths of excitations from the gearbox, revealing an increased potential of LSS Couplings especially for integrated drivetrains. Detailed numerical investigations are performed in order to understand and quantify the usage of a LSS coupling for lowering sound power levels of a WT.

Comparison of Transfer Path Characteristics for different Wind Turbine Drivetrain variations

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Abstract: To reduce acoustic emissions of a wind turbine (WT), the source of the vibrations (e.g. blades, gearbox), the emitting surfaces (e.g. blades, tower, nacelle cover) and the transmission between the source and surface have to be studied. The focus of this paper lies on a method to identify relevant transfer paths between the WT drivetrain and the sound-emitting surfaces and their respective contribution. The identified transfer paths can be used to improve turbine acoustics, especially by identifying problematic transmission areas. This paper will cover the application of transfer path analysis methods for different wind turbine drivetrains. The method will be applied to an MBS model of a 3MW turbine. Different Bearing arrangements of the drivetrain and their influence on the Transfer path are compared. With the result of the TPA, developers will be able to determine critical contributions to the tonal behavior of the turbine and optimize either the transfer characteristics or the excitation specifically responsible for tonal behavior. The methods described can be applied to field measurement as well as an MBS-Model of the turbine to be able to optimize transfer characteristics during development.

Experimental identification of relevant drive train vibration modes for tonality mitigation of wind turbines

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Abstract: Acoustic tonalities which exceed legal regulations may lead to restricted wind turbine operations and thus reduce yield. They arise for example from gear mesh vibration of planetary gearboxes, which are used in many wind turbine drive train designs. Passive or active vibration control measures at the drive train can be applied to reduce acoustic tonalities. The key to success of such mitigation measures is to understand which vibration modes of the drive train need to be reduced in order to achieve acoustic reductions. This paper proposes two experimental approaches to identify acoustic-relevant drive train vibration modes. The approaches are described in detail and their characteristic advantages and efforts are discussed.

Noise and Vibration Analytics Framework and its Practical Application to Achieve a Tonality Free Wind Turbine and Power Train Design

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Abstract: NVH behavior is often a key contributor to a successful wind turbine powertrain development.

In an early design stage NVH strategic decisions need to be taken, often with a limited amount of available data and within a strict time frame. As the development proceeds, model input data gets refined and model complexity increases. To cope with this evolution, it is key to have an automated and validated tool chain in place.

In this paper the concept of the NOVA (NOise and Vibration Analytics) framework is explained, and a practical example is shown. This tool is developed and used at ZF Wind Power for predicting tonalities. It manages different tonality risk mitigation models, by means of a version-controlled database. In this way, ZF Wind Power can manage and mitigate tonality risks – together with its customers – based on detailed simulation models in all development stages.

Main Bearing and Shaft

Development and Layout of Two Innovative Hydrodynamic Rotor Main Bearing Designs

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Abstract: Roller bearings as rotor main bearings (RMB) are known to cause high costs in case of premature failure as the whole wind turbine drive train must be disassembled to exchange the bearings. Alternatively, hydrodynamic bearings can be designed as segmented pad bearings, offering the opportunity to exchange individual pads with reasonable effort in a maintenance case. So far, no committed design criteria exist to create a robust hydrodynamic RMB design considering the complex dynamic load and speed situation. Since design criteria are missing, a high-performing and efficient software tool is needed to analyze bearing concepts in detail at an early stage to assess the expected performance.

To achieve the best possible design, design parameters like geometry, clearance and pad contouring need to be varied and rated regarding their influence on target parameters like pressure distribution, friction, temperatures and wear. For practical application, the RMB design must be verified and validated by extensive and thorough experimental analysis. Therefore, two different and fully instrumented RMB design solutions for a single and three-point suspension are tested on a 1 MW test rig. Various operating conditions like idling, start-stop and energy production are tested, measured, analyzed and compared to the calculated results to validate the simulation models and to assess the model quality of the simulation.

Advanced, numerical simulation of the bearing ring creeping failure mode and comparison with experimental test results for rotor main bearing applicationssensing

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Abstract: The increasing power of multi-MW wind turbine applications and the simultaneous growth in the overall bearing size is a major challenge for the product development process in order to ensure the service lifetime. In particular the failure mode “ring creeping”, which can lead to fretting corrosion and/or abrasive wear between bearing ring and shaft (respectively housing), is design-critical for non-bolted large-sized diameter bearing applications. Ring creeping in general refers to a failure mode caused by a bearing ring rotating relatively to its adjacent component during operation. This ring movement as a result of the accumulated microslip occurs due to a partial reduction or even an entire loss of the contact pressure within the contact gap. This can be caused either by the roller elements itself (roller induced) or by the deformation of the adjacent drivetrain components (structural induced).

Coping with these challenges, an advanced simulation method based on finite element analyses has been developed in order to purposefully take into account both root causes. To facilitate an analysis of the physical creeping effect on the micro scale level while at the same time modelling the relevant drivetrain processes on a component scale level, the parameters of the FE model are to be defined suitably. In particular the friction coefficient at the contact interface between bearing ring and adjacent component - ultimately representing the “trained” or run-in contact conditions - has an essential impact. In order to consider this effect, a creeping test rig based on component-like specimen has been developed. Experimental results with respect to (i) measured creeping parameters such as creeping distance and (ii) the variation of the friction coefficient due to run-in effects are shown. Ultimately, both experimental and numerical results will be discussed and the general capability of the advanced numerical simulation method for the application on project task is shown.

Dynamic modelling of slip in the spherical roller main bearing of a 1.5 MW wind turbine

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Abstract: This paper considers the problem of the dynamic modelling of macro slip in spherical roller bearings. By revisiting the fundamental physics which drive these systems, potential issues in existing models have been identified. Furthermore, in pure rolling conditions it was found that governing differential equations become “stiff”, requiring the use of implicit methods of time integration. The problem of individual roller macro slip in a wind turbine main bearing is then investigated using a simplified representation of system dynamics. Model results indicate clear links between slip/friction and the operational strategy of the wind turbine, as well as significantly higher frictional effects in the downwind main bearing row. Due to modelling simplifications, these results should not yet be considered conclusive, with further work required.

Cost Efficient Design of Wind Turbine Main Bearing Systems

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Abstract: In the wind turbine generator market, many different main bearing arrangements and types exist. In particular, three-point and four-point suspension, self-retaining momentum bearings, separated bearings, or even pre-assembled bearing units are common in practice. Besides the bearing arrangement, the application of different types of rollers, like tapered, cylindrical, or spherical roller variants exist. State-of-the-art bearing design work mainly focusses on single component optimization within a given drive train concept.

For leading developers and suppliers of main and blade bearings for wind turbines, it is essential to understand the influence of the different bearing types and related drive train concepts on both the technical and the commercial performance of the overall wind turbine generator set. In this context, thyssenkrupp rothe erde together with engineering service provider IME Aachen GmbH and the research institute MSE of the RWTH Aachen University have developed an estimation method for the manufacturing costs of different wind turbine main bearing systems. The method comprises a semi-elastic multi body system approach which is able to consider over-determined arrangements and pretension in the pressure calculations of the bearing system. It can be utilized for early estimations and fast comparisons of costs and technical characteristics of different bearing arrangements. A software program implementing the method allows the multidimensional optimization of the system costs for specific design parameters.

The contribution provides insight into the developed method with a design of experiments case study of main bearing system designs for different wind turbine concepts in the 6-16 MW range. Hereto, case specific cost and performance advantages of different bearing system designs are evaluated to illustrate the potential of drive train system optimization, resulting in cost-optimal designs, which fulfill the technical requirements for the different turbine configurations.

Electrically Induced Loads from Generator

Reduction of Wind Turbine Gearbox Damage Risk due to Electrical Faults via Drivetrain Design Optimization

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Abstract: Over the lifetime of a wind turbine (WT) it is likely that several electrical faults occur. Electrical faults may induce significant electromagnetic generator torque excitations. The torque excitations are transferred to the gearbox components and lead to dynamic load changes as well as changes in the speed of rotation. Dynamic load changes in combination with changing rotational speeds might lead to gearbox component damage. Gearbox component damage is the main driver for WT downtime due to the high time to repair the fault. Especially the components of the high-speed stage (HSS) are prone to failure. This paper presents a method for introducing gearbox component design optimizations in order to reduce the damage risk during electrical faults. Via profile shift the HSS safety against scuffing cannot be further increased compared to the reference. The HSS safety against micropitting can be increased via profile shift by max. 41% and the safety against tooth flank fracture on the HSS by max. 3% compared to the reference. Via profile modification the HSS safety against scuffing can be increased by max. 14%, the HSS safety against micropitting by max. 8% and the safety against tooth flank fracture on the HSS by max. 8% compared to the reference. Via roller profile optimization the smearing risk on the HSS cylindrical roller bearing can be reduced by max. 3% compared to the reference. Thus, on the basis of two exemplarily analyzed electrical faults, this paper shows that gearbox component design optimizations can significantly reduce the gearbox damage risk during electrical faults.

Effect of generator torque ripple optimization on a geared wind turbine drivetrain

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Abstract: In this paper, the load effect of torque ripple reduction of a wind turbine generator is analyzed on the high-speed shaft gear stage and high-speed shaft bearings, which are the nearest components to the generator. Two generator designs with different torque ripples for the NREL 5-MW reference wind turbine are considered. A decoupled analysis method is used, where global loads and torque ripple loads are used as input to a multibody model of the drivetrain in order to analyze the gear and bearing load response. Two different multibody models are considered in this work; one traditional decoupled model without generator inertia and one model with additional coupling and generator. For the model without generator inertia, statistical changes are observed for the load case with the largest torque ripple. This subsequently causes a limited increase in gear root bending damage and bearing fatigue damage. For the load case with the smallest torque ripple a limited statistical change and no damage increase is observed. For the model that includes the coupling and the generator, no statistical changes are observed between the simulation with the largest torque ripple and the smallest torque ripple. This is due to the torque ripple load that is expended to overcome the large inertia of the generator.

Investigation on the Impact of Electrical Faults on the Loads and Exposures of Wind Turbine Gears

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Abstract: For the design of a wind turbine, it is necessary that the design process takes into account the stresses of real operation to a high degree of detail so that targeted dimensioning can be carried out. Depending on its design, the drivetrain of a wind turbine includes a gearbox that connects the rotor to the generator. During operation of a wind turbine, transient load conditions can occur due to loopback from the power grid and faults in the frequency converter. The influence of the resulting stress and possible damage to the gears used in the gearbox is unclear in the design phase. While the stresses on the gears can often be simulated with a high degree of accuracy for constant operating conditions and can thus be integrated into the drivetrain design, this is not the state of the art for dynamic load conditions. The objective of this report is a method for considering dynamic loading events in the design of the cylindrical gear stage used in wind turbine gearboxes using a coupled multi-body simulation and a finite element based tooth contact analysis. Afterwards the method

is used to quantify the stress on the tooth flank and tooth root due to special electrical events such as short circuits between the frequency converter and generator or power grid faults for various converter designs. The simulation analyses show that different converter concepts have different effects on the resulting gear load during electrical faults, but are not significantly decisive for the accumulated damage due to elastic material behavior between generator and gear.

Electrical Components and Energy Systems

Assessing the Influence of Lightweight Generators on Substructure Cost and Levelized Cost of Energy

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Abstract: It is expected that lightweight drive train systems for large wind turbines can reduce overall levelized cost of energy (LCOE) compared to conventional designs, particularly through a less robust and therefore lower-cost turbine substructure. Representing a major share of drive train mass, the focus of mass reduction efforts concentrate on the generator. In order to assess the influence of specific lightweight generator designs on overall LCOE, a techno-economic software tool was created which feeds generator mass into the LCOE calculation through the design and capital expenditure (CAPEX) calculation of an appropriate wind turbine substructure. A case study was carried out, comparing a direct drive design featuring a permanent magnet generator with ring architecture and large diameter—resulting in significantly low mass and low CAPEX—to a reference turbine with conventional drive train design. The results show that a relevant LCOE reduction could be achieved, but generator mass reduction and substructure mass and consequently CAPEX reduction are highly disproportionate due to technical substructure design constraints. It is indicated that the assessed lightweight design has a high potential to economize on lightweight design decisions to reduce its CAPEX and in consequence overall LCOE even further.

A discussion on the characterization of AC grid emulators by apparent power rating and short-circuit power

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Abstract: AC grid emulators are electrical test systems based on power electronic converters usually installed at dedicated test facilities. They enable the testing and validation of renewable power generation units, such as wind turbines, in a controlled environment under repeatable conditions. This concept of testing reduces the time to market for wind turbine systems and finally increases the reliability needed for large scale power generation.

The test capacity of AC grid emulators is characterized amongst others by the apparent power rating and the short-circuit power of the installed components. The power capability is mainly determined by the converters power rating which clearly sets the limits for rated and overload operation of the DUT. In contrast, the meaning of short-circuit power is manifold. In this context, short-circuit power is a measure for voltage stability and grid strength. Furthermore, the short-circuit ratio is a traditional parameter for wind turbine manufacturers.

Therefore, on the one hand, the natural short-circuit power of an AC grid emulator is solely determined by the natural impedances of the passive components. On the other hand, AC grid emulators can control the voltage depending on the injected load current. Thereby they emulate an arbitrary virtual impedance or short-circuit power towards the DUT. The concept of natural and virtual impedance and short-circuit power may lead to misunderstandings, since the virtual short-circuit power can be much bigger compared to the power rating of the installed converters.

The following discussion is aimed to clarify the implications of those concepts. It presents the impact of converter power and passive components on the power capabilities provided to the DUT. Further dimensioning criteria are discussed. Switching frequency is presented as one main design criterion with impact on component ratings and test performance. Finally, the capabilities and limitations of virtual impedance control are outlined.

Impact of DC-Link Brake Chopper Design on the LVRT Behavior of Full Scale Converter Wind Turbines

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Abstract: Wind turbines (WTs) are loaded by the wind and by the electrical grid. A low voltage ride through (LVRT) is a special load case for WTs, which can be critical for their drivetrain. They are usually less severe for WTs with a full-scale converter (FSC); however, in some cases there are still loads observable in the mechanical drivetrains of WTs with FSCs. Different aspects like the brake chopper design, the control and specifications of the grid side converter (GSC) as well as the grid and fault parameters affect these loads. In this paper, three different LVRT behaviors of a WT with a squirrel-cage induction generator (SCIG) and a FSC were investigated via simulations. In the worst case, a sharp peak in the electromagnetic torque of the generator after fault clearance is possible. The cause lies in the GSC control, especially the phase-locked loop (PLL), and can also be influenced by adjusting the control parameters, brake chopper and filter design. The resulting mechanical drivetrain torque, on the other hand, is increased by only 2.9% for a very short time. Thus, the loading of the mechanical drivetrain components is only slightly increased. Therefore, the risk of damage to the mechanical components of the FSC WT due to grid faults is relatively low.

ISA-HyPLAN, a tool for system simulation of green hydrogen P2G plant concepts to facilitate implementation taking technical and economic aspects into account

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ISATEC GmbH

Abstract: Overcoming obstacles to initiate and realize Power-2-Hydrogen projects: this is why we have developed ISA-HyPLAN. With our planning tool we are able to support power and hydrogen producers, investors and consumers in the technical and economic project planning of Power-2-Hydrogen systems. ISA-HyPLAN simulates the entire system, from power generation from renewable energy sources to electrolysis technologies and consumer requirements. The result: an economically optimized concept of decentralized hydrogen production which is technically customized regarding location and intended use. To illustrate the capability of the tool, the application to a specific project, Wind2Move, is presented.

Hil Testing Validation

HiL testing of wind turbines – from research to standards

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R&D Test Systems A/S

Abstract: This contribution outlines, how Hardware-in-the-loop (HiL) systems for full-scale wind turbine testing have evolved from a research subject to one of the key components for test bench-based turbine certification over the past decade. We look at technical hurdles and milestones throughout this journey, the status of the international standards, such as IEC 61400-21-4 and how this strengthens the role of HiL systems. Finally, we'll look at the future and how certification and validation will be further digitalized and what this implies for our industry.

HiL-Grid-CoP: Electrical type testing of wind turbines on the minimum system using a test rig

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Abstract: Recently, the wind energy community intensified its efforts in speeding up the time-to-market of new wind turbine prototypes. OEMs are showing a growing interest within laboratory testing and certification through minimal system testing, further defined as the ability to isolate and test specific entities, i.e., generator, transformer, converter, and control plus protection system. In the laboratory, wind conditions can be set to test specific functions in a reproducible and deterministic manner, decoupling the length of campaigns from local weather conditions. Due to the ongoing maturation of minimal system testing, it is important to show how testing procedures in a laboratory exhibit comparable results to the field. In this context, Fraunhofer IWES has designed and commissioned the HiL-Grid-CoP (Hardware-in-the-Loop Grid-Compliance) test bench to enable the electrical certification of minimal wind turbine systems and the testing of new prototypes, especially with high-speed generators. Generally, load conditions at the test rig must be dynamically adjusted to compensate for missing mechanical components, e.g., the rotor, tower, and gear box. Focusing on mechanical emulation, the authors present their experience and results from the last two test campaigns performed within the project HiL-Grid-CoP with Nordex Energy SE & Co. KG and Vestas Wind Systems A/S. The paper emphasizes the HiL-framework employed to replicate field rotational behavior. It is explored how a wind turbine model must be adapted to operate in real-time providing high-fidelity setpoints to the drive. Additionally, it is shown how to compensate for the inherent test bench torsional dynamics.

Experimental validation of Digital Twin for virtual load sensing in wind turbine drivetrains

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Abstract: This paper presents a Digital Twin for virtual sensing of wind turbine aerodynamic hub loads, as well as monitoring the accumulated fatigue damage and remaining useful life in drivetrain bearings based on measurements of the Supervisory Control and Data Acquisition (SCADA) and the drivetrain condition monitoring system (CMS). The aerodynamic load estimation is realized with data-driven regression models, while the estimation of local bearing loads and damage is conducted with physics-based, analytical models. Field measurements of the DOE 1.5 research turbine are used for model training and validation. The results show low errors of 6.4% and 1.1% in the predicted damage at the main and the generator side high-speed bearing respectively.

Influence of the impact time of a WEC trigger on failure risk

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Abstract: Rolling bearings can fail due to White Etching Crack (WECs) before reaching their calculated rating life, if so-called additional loads, like electrical currents or very high friction energy, are applied on the bearing beside the Hertzian rolling contact stresses. The WEC-critical operating conditions often do not occur over the whole operating period. Sometimes they are recognized and largely mitigated. Under these circumstances, it is unclear whether the bearings are then already irreversibly damaged and will finally fail. To clarify the pre-damage due to additional loads, WEC bearing tests on different WEC test stages with varied impact time of the additional load were made and will be presented. The results are used to divide the entire WEC formation process into a damage phase, in which the additional load is present and a subsequent fatigue phase, in which the additional load is no longer essential. It could be shown that the higher the product of additional and main load the shorter the WEC damage phase. Detectable WECs occurred relatively late in the fatigue phase and therefore cannot be used as indicator of an irreversible pre-damage. Although no WECs are detectable, the bearing may still be irreversibly pre-damaged.

Validation and Calculation

Structural digital-twins during the design process

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Abstract: In an early design state often fundamental design decisions need to be taken. As Torque Density Increases (TDI) and cost are very strongly related to the gearbox or drive train concept, a first prediction can already be done quite well with analytical tools. However, for new multi-planet gear concepts, the torque density of gears has more than doubled within the last decade. On the other hand, it means, that by keeping the same strength limits, the material usage grade has doubled as well: more material is active in transforming torque and rotation speed. The relative loading increases and thus the relative deformation of components, sub-systems and system get more into focus. To answer questions on reliability, numerical structural mechanical digital twins (SDT) up to full system level are used for identifying and eliminating potential risks and to optimize the working performance of gears and bearings over the total torque range. In the given paper, the status of today's simulation technologies and their capabilities are shown and an outlook on future developments is given.

Key Applications of FEA and MBS in Wind Turbine Gearboxes

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Abstract: The development of gearboxes for wind turbines is more and more driven by load density, new drivetrain concepts and acoustic limits. The need to build a lightweight and still highly reliable gearbox raises new questions and higher requirements to the dimensioning and calculation of the gearbox components. To answer these questions, new cutting-edge simulation methods must be applied.

The most important simulation methods are the finite element analysis (FEA) and the multi body simulation (MBS) for static and dynamic questions. The topics that are covered by these methods become more and more complex. On the one hand this leads to very specialized simulation models that make use of top-level features of the respective simulation methods. On the other hand, there are also topics that require the advantages of both methods, leading to growing intersections between FEA and MBS.

Today questions like load sharing and load distribution can be answered by both methods. This leads to growing intersections between both simulation approaches. In future there maybe is something like a meta model that allows combined and platform independent FEA and MBS simulation.

Comprehensive investigation of wind turbines using detailed MBS models

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Abstract: The high costs for the development, erecting und operation of wind turbines are connected to very high expectations for a reliable and low-maintenance operation and require a precise knowledge of the loads and stresses to be expected. The transfer of knowledge from smaller wind turbines and possibly other concepts succeeds only to a limited extent. Rather comprehensive simulation approaches to determine wind loads, operational conditions and possible resonances are already used since many years. By means of simulation models, the natural frequencies can be determined and compared to possible excitations. The simulation of the operation of the wind turbine under different wind speeds allows the calculation of component loads as a basis for the further design process. The paper concentrates on the possibility of using multibody-system simulation models in the design process of gearboxes for wind turbines and the associated dynamic properties of the complete system by the example of the 15MW reference wind turbine of the National Renewable Energy Laboratory (NREL). The comprehensive factors which influence the load distribution in the gearing of the first planetary gear stage require a detailed consideration of the elasticity of all relevant components. Based on the developed gearbox design and a detailed multibody-system simulation model, the influence of the level of detail of the model on the resulting natural frequencies and the occurring load distribution in the gearing of the planetary gear stages can be discussed. The present results show that findings on the required level of detail of simulation models cannot be applied to new turbines independently of the power class.

Interdisciplinary Optimization of Cast Iron Components in Wind Turbines

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Abstract: The continuously rising demand for renewable energies leads to increased installations of large-volume wind turbines. While the current power-to-weight ratio of up to 20 metric tons of cast iron per megawatt is stagnating, cast iron components of modern wind turbines are facing new challenges in terms of weight, manufacturability and castability. These challenges can be addressed by the systematic use of interdisciplinary optimization approaches to reduce component weight and increase the local component utilization.

In order to meet the requirements for modern cast iron components, this interdisciplinary approach must employ methods from the fields of casting simulation, micromechanical analysis, topology optimization and strength assessment. Here, the casting simulation is used for the determination of local microstructure descriptors, which subsequently are used in micromechanical shakedown analysis for the estimation of the local microstructure dependent fatigue strength. In parallel to the fatigue strength estimation, a topology optimization is performed iteratively in combination with a castability analysis. The component strength is assessed using a strength assessment approach based on the previously determined local material properties in combination with the topology optimized component.

In this study, the overall concept of the proposed interdisciplinary approach is presented and requirements for the application of such an approach are formulated. Use cases of this study are components of ductile cast iron, such as torque arm or main shaft, or of austempered ductile iron, such as the planetary carrier. Using these demonstrators, the potential and limitations of the presented approach are determined and overall potential of the concept in terms of weight reduction of large cast iron components is outlined.

Selective assembly applied in planetary gear stages

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Abstract: Selective assembly processes are already used in various applications to achieve higher accuracy or to limit the variations caused by geometrical tolerances. ZF Wind Power has implemented the Selective Assembly principle to achieve better load sharing between planets in higher-loaded multiple-planet planetary stages. Two possible approaches are considered: in case of multiple contributing parts in the tolerance chain, a high number of assembly combinations will be possible, each having a specific positional deviation (e.g., a 5-planet system with no back-up parts will have 1.7 million possible combinations). In case only one component is the main driver, geometrical variation has to be minimized by selecting the best-matching set of components out of a larger group of available parts. The first approach is called Selective Assembly, the second Planet Sorting. This article gives an overview of both the Selective Assembly and Planet Sorting processes: the theory behind the processes, a specific calculation example, the validation of the process, the implementation of the process in the different involved departments throughout the organization and the effect on gear rating assessment.

ML and AI in Wind Turbines

Load Monitoring of Main Bearings in Wind Turbines

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Abstract: The premature failure of wind turbines reduces competitiveness compared to other energy sources. Especially the failure of the main bearings results in high costs and downtimes, as the rotor needs to be demounted for an exchange of this component. Load monitoring systems can make a significant contribution to monitoring this component. However, most load monitoring systems do not take into account the main bearing loads in particular as there is no commercially applicable measuring system for this purpose. This work shows how main bearing loads can be estimated using virtual sensors. For this purpose, linear regression models are trained with simulation data considering strain or displacement signals. It is analyzed which signal types and simulation techniques achieve the best accuracy.

Artificial Intelligence for Sustainable Control of Wind Power Drives

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Abstract: Many failures of wind turbines are due to drive failures caused by pitting. Each failure can be associated with high repair costs and time-consuming repair work. This particularly applies to offshore facilities. For these reasons, increasing the remaining useful life of wind power drives is essential to leave a minimal ecological footprint by simultaneously increasing power output. Pitting damage occurs first on the weakest tooth. Artificial Intelligence is used to apply a local load reduction to a pre-damaged tooth and delay degradation. The other intact teeth compensate for the load reduction in order to achieve a constant average power. To increase the service life of wind power drives and to avoid unexpected failures an adaptive operating strategy can be implemented. With a test gearbox the adaptive operating strategy is examined on a test bench. The test gearbox is equipped with test gears with varying degrees of pre-damage. The objective of the examinations on the test gearbox is to detect pitting damage at the earliest possible stage. The earlier damage is detected, the greater the potential for increasing useful life. For detection, multiple high frequency acceleration sensors are integrated in the gearbox. Using machine learning approaches, the vibration data are analyzed. By means of anomaly detection damage can be identified during operation. Using torque control on the test bench, the load on pre-damaged teeth is minimized depending on the detected damage. In summary, the findings on the test gearbox will provide fundamental knowledge that will enable the implementation of the adaptive operating strategy in wind power drives.

Data-driven Virtual Sensor for Online Loads Estimation of Drivetrain of Wind Turbines

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Abstract: Data-driven approaches have gained interest recently in the field of wind energy. Data-driven online estimators have been investigated and demonstrated in several applications such as online loads estimation, wake center position estimations, online damage estimation. The present work demonstrates the application of machine learning algorithms to formulate an estimator of the internal loads acting on the bearings of the drivetrain of onshore wind turbines. The loads estimator is implemented as a linear state-space model that is augmented with a non-linear feed-forward neural network. The estimator infers the loads time series as a function of the standard measurements from the SCADA and condition monitoring systems (CMS). A formal analysis of the available data is carried out to define the structure of the virtual sensor regarding the order of the models, number of states, architecture of neural networks. Correlation coefficient of 98% in the time domain and matching of the frequency signature are achieved. Several applications are mentioned and discussed in this work such as online estimation of the forces for monitoring and model predictive control applications.

Reliability and Maintenance

Intelligent Power Train for reducing LCoE in Wind Business

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Project House (ICD)

ZF Group

Abstract: The Wind Business continues to put efforts into reducing the Levelized Cost of Energy (LCoE). Predictive Condition Monitoring of wind gearboxes is a major contributor which helps to define the profitability of the business case and reduce LCoE.

Within ZF, the Intelligent Powertrain concept aims to integrate several new functionalities in our products, especially our gearboxes, to enable and facilitate Advanced Condition Monitoring. The presentation will focus on one of the ZF internal developments, a new approach for Vibration Condition Monitoring of journal bearings in planetary gear sets. With this offering ZF contributes to proactively reducing the financial risk caused by potential bearing damage.

Method to Design a Generalizable Sensor System for Estimating Transmission Input Loads of a Wind Turbine

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Abstract: Despite the ongoing trend to increase the rotor diameters and heights of wind turbines and hence the load situation on the drive train and the main gearbox, current condition monitoring systems do not record the 6-degree of freedom (6-DOF) input loads to the transmission due to the high costs of existing measurement technology. In order to provide future condition monitoring systems transparency into the actual load situation experienced by the main gearbox of a wind turbine (WT) during operation, a methodology for developing virtual load sensors capable of estimating gearbox input loads in 6-DOF is developed. The methodology is realized through analyses of data resulting from simulations and accelerated real-world tests of different wind turbine drivetrain designs. The drivetrain of the Vestas V52 WT is used for the first application of the method. A multibody simulation (MBS) model of the V52 WT is developed and subjected to simulated wind fields covering design load cases from the IEC 61400-1 standard in aeroelastic simulations. The resulting simulated data is used to train machine learning models on the targeted tasks of 6-DOF virtual load sensing, screen sensor types and locations on the drivetrain to perform the virtual sensing, and to design experiments for accelerated load testing. The approach provide the necessary preparation for the collection of realistic sensor data for the development and testing of machine learning-based virtual sensors using the 4MW WT system test bench at the Center for Wind Power Drives.

Fleet-wide analytics on field data targeting condition and lifetime aspects of wind turbine drivetrains

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Abstract: Drivetrain failures result in the largest downtime per failure among the different turbine components. To minimize O&M costs, it is therefore essential to be able to anticipate failure events sufficiently in advance such that scheduled maintenance can take place. Moreover, a root cause for the failure should be identified, allowing to incorporate this knowledge in future design iterations, thereby increasing the reliability of the machine. In offshore wind energy, high-frequency SCADA (1Hz) and vibration data (>20kHz) are becoming increasingly available to monitor machine performance and health. This paper presents a twofold approach for monitoring drivetrain health and load history based on these two data sources. First, SCADA data is used to extract different design load cases (DLCs), described in IEC 61400-3. Second, vibration data is used for advanced signal analysis to detect potential incipient bearing or gear defects in the drivetrain. It is shown that the efficacy of this vibration analysis is further enhanced by combining it with operating condition information from the SCADA data.

Design for Reliability: Full Probabilistic approaches for the Wind Industry

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Abstract: For about the last decade, the wind industry has implemented reliability engineering and methods for reliability assessment. Meanwhile a framework for gearbox reliability assessments is being developed by IEC Joint Working Group 1. The present publication provides a brief retrospective and gives an overview on the reliability engineering context. Furthermore, it provides application examples for full probabilistic approaches and points out potential fields for future research. It reveals opportunities and weak points of applied methods and gives an outlook on future methodology improvements, such as by including field data. Finally, the paper suggests a reliability strategy for the wind industry.

Development of process and toolkit for uptower replacement of main shaft spherical roller bearing

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Abstract: One of the most widely used drive train concepts is the three-point bearing arrangement, with a spherical roller bearing used as the front rotor bearing. While this design has certain advantages, such as a simple structure, it also has disadvantages. Due to the axial thrust, primarily the downwind row of rollers is load-bearing, resulting in unfavorable load distribution and bearing kinematics.

For this reason, damage to the spherical roller bearings is occurring at an early stage. As the damage progresses, the bearing must be replaced, which is a cost-intensive process acc. to the current state of the art. An expensive high-capacity crane is necessary to dismantle the entire rotor and drive train. The drivetrain needs to be refurbished in a factory hall. The revised drive train is then reassembled by crane.

Eolotec GmbH has started a research project together with Schaeffler to develop a new concept for main bearing replacement. The aim is to develop a process and tools that allow a bearing replacement that is independently of the weather, while at the same time reducing costs by 20 – 40 %. Since it is not necessary to dismantle the entire drive train, a crane is not required.

During the replacement, the rotor and drive train remain in place so that the weight and wind loads are supported by a holding device. The hole drive train is slightly lifted, so that the bearing housing can be removed from the main bearing. The bearing is dismantled. After mounting a new optimized bearing, the original bearing housing is slid back.

After the production of the devices, the main bearing replacement was successfully carried out on ground as part of a prototype assembly. The test in a whole nacelle on ground demonstrated the basic feasibility. A prototype of the optimized bearing is in operation since 2020 and provides measurement results. The next step is to replace a main bearing on tower, which is already planned and shall be done before the conference will take place.

Nacelle Testing

An Innovative Methodology for Full Load Testing of Wind Turbine Drivetrains on a Test Bench

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Abstract: Today's nacelle test benches are facing several challenges regarding meeting the increasing demands of modern wind turbines, which have been growing rapidly in operational range, size, and complexity. These challenges include reproducing the demanded extreme loads, dynamic load bandwidth, power capacity, and cost of testing. This contribution presents a new testing approach to tackle some of the aforementioned challenges faced by existing nacelle test benches. The method is demonstrated in a case study involving experimental measurements and simulations of a multi-megawatt wind turbine drivetrain recently tested at the DyNaLab of Fraunhofer IWES. By combining high-fidelity simulation models and partial load tests, the proposed approach has shown high potential for representing the full load response of a wind turbine nacelle. The proposed testing methodology has potential for resolving some of the challenges being faced by modern test benches in terms of obtaining full load responses on a nacelle test bench with a possibility of reducing the cost of testing.

Direct measurement of input loads for the wind turbine drivetrain under test on a nacelle test bench

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Abstract: Modern wind turbines have some of the highest levels of torque and non-torque loads of all industrial sectors. These high loads present a great challenge for the design of wind turbines. On a nacelle test bench, the wind turbine drivetrain can be tested and validated against the design. It is therefore important to measure the correct level of each load and all its dynamic behaviors during the test. The best way to achieve this is to measure the loads directly in front of the drivetrain. This paper presents a method of direct load measurement on the shaft adapter which connects the drivetrain to the test bench. The technical solution and some important details about the instrumentation on the adapter are also presented. Methods of signal nulling as well as signal conversion from raw signals to the loads are compared as well. The measurements obtained are then compared with the applied loads from the test bench which show good agreement. As a special case, the torque measurement is validated and calibrated up to 5MNm by means of a state-of-the-art torque transducer.

Traceable efficiency determination of a 2.75 MW nacelle on a test bench

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Abstract: In this paper, the efficiency of a 2.75MWnacelle drivetrain on a test bench was determined traceably at various load points. For this purpose, so-called transfer standards for mechanical and electrical power measurement were additionally installed and integrated into the nacelle drivetrain. As torque measurement contributes greatly to the overall uncertainty, the static torque calibration was expanded to include additional influences present under rotation. An overall system efficiency of 89% was measured in the high torque and high speed range. The relative expanded measurement uncertainty for efficiency determination was between 0.30% and 0.72% over the entire operating range. Both the efficiency and the relative expanded measurement uncertainty were calculated for each operating point.

Turbine and Park Control

Improving wind farm power tracking control by considering power train degradation and using database approach

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Abstract: With the coming installation of hundreds of GW of offshore wind power, penetration of the inherent power fluctuations into the electricity grid will become significant. Therefore, the use of wind farms as power reserve providers to support the regulation of the grid's voltage and frequency through delivering a desired power is expected to increase. As a result, wind turbines will not be necessarily delivering the maximum available power anymore – known as curtailed or derated operation – and will have to be able to deal with time-variant power demand. For this purpose, power setpoints from the grid are dispatched at the farm-level and then tracked at the turbine-level under the constraint of available power in the wind (known as active power control). The idea of this work is taking advantage of the additional degree of freedom lying in the power dispatch between turbines when operating in curtailed conditions. As failure of power train system components is frequent, costly and predictable, we seek to introduce power train degradation into the farm control objectives. To this end, a data-driven model of drivetrain fatigue damage as function of wind conditions and derating factor adapted to the farm active power control objective function is developed based on the pre-analysis of single-turbine simulations and degradation calculations, where the increased turbulence intensity due to wind farm wake effect is also considered. The proposed analytical power train degradation model is computationally efficient, can reflect the fatigue damage of individual gears and bearings in the overall power train life function and in contrast with high-fidelity models can be easily adjusted for different drivetrain configurations. A case study on the TotalControl reference wind power plant is demonstrated.

Challenges of Applying Model-Based Predictive Wind Turbine Control in the Field

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Abstract: Wind energy plays a major role in renewable energies. The increasing demand for wind energy has caused wind turbines to grow steadily larger, which means that the control objectives are no longer solely to maximize the energy produced, but also to actively control mechanical loads, among other objectives. Model-based wind turbine control, in particular model predictive control (MPC), has been the focus of research for the last decades. Nevertheless, only a few practical investigations of MPC for wind turbines in field tests have been reported so far.

This paper will highlight some key challenges and pitfalls that arise when practically applying MPC for wind turbines. We render these key points based on the experience of a recently conducted field test and discuss possible solutions for these challenges. In doing so, we highlight the following three critical areas: Firstly, we show how critical nonlinear properties of the wind turbine model can be taken into account in the design and practical operation of an MPC system. In particular, we address the highly varying sensitivity to the pitch angle and the dynamic responses of the rotor speed and mechanical loads to the actuator commands over the partial and full load ranges. Secondly, we discuss the problem of having limited computational capacities on real-time platforms, restricting the possible complexity of the MPC algorithm. Lastly, we show how some safety aspects decisively influence the design and operation of the control algorithm.

Practical Aspects of Testing Wind Turbine Control Algorithms on Nacelle Test Benches

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Abstract: The validation and certification of wind turbines (WT) on nacelle test benches (NTB) is becoming increasingly important in the development process. While for certifiers the advantage lies in controlled test execution, for development departments it lies in testing as many system components as possible in a quasi-final prototype. However, the question arises which practical conditions must be fulfilled so that statements can also be made about WT control. In addition to the errors induced by a mechanical Hardware in the Loop (mHiL) system, the dynamic interactions between the WT controller and the NTB controller applying the mHiL concept are of interest. This analytical work based on simulations aims to systematically investigate how realistic the control behavior of a WT operated on a NTB is. For this purpose, the nominal behavior of a WT is compared with the operation on a NTB under realistic conditions and the resulting differences are subsequently reproduced in a synthetic load case. Finally, the differences are analyzed in terms of system theory. It is found that a frequency-dependent distorted behavior caused by operating the WT on a NTB is responsible for strong deviations compared to the WT operation in field. In the controller configuration studied, gain amplifications up to 5.17dB are identified. The distortion is not exclusively caused by the mHiL closed loop behavior, but results from the interaction of all subsystems in both control loops. Therefore, its behavior is identified as a function of the system and controller parameters of both the WT and the NTB.

Influence of Drivetrain Efficiency Determination on the Operation Point Control of Wind Turbines

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Abstract: Decreasing the levelized cost of energy is a major design objective for wind turbines. Accordingly, the control is generally optimized to achieve a high energy production and a high-power coefficient. In partial load range, speed and torque are controlled via the generator torque but the rotor torque determines the power coefficient of the turbine. High uncertainties for the uncalibrated low-speed shaft torque measurement and varying drivetrain efficiencies which depend on the speed, load and temperature lead to a torque control error that reduces the power coefficient of the wind turbine. In this paper the rotor torque control error and the impact on the power coefficient of wind turbines is quantified. For this purpose, the variation of drivetrain efficiency is analyzed. An efficiency model for the wind turbine drivetrain is build and validated on the test bench. Then, the influence of the drivetrain speed, torque loads, non-torque loads, and temperature on the efficiency is quantified. Finally, the influence of the rotor torque control error on the power coefficient was simulated with an aerodynamic model. The results show that of all examined influences only torque and temperature significantly impacting the efficiency leading to rotor torque control errors that reduce the power coefficient and consequently increase the levelized cost of energy. Improved efficiency measurement on WT test benches or drivetrain efficiency modelling can reduce the rotor torque control error and therefore decrease the LCOE.

Load mitigation and power tracking control for multi-rotor turbines

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Abstract: A model-based feasible control strategy for multi-rotor systems is presented, pursuing two control objectives simultaneously: Mechanical loads on the main tower are to be mitigated, and an externally determined power change is to be followed to obtain fast power reference response in power systems. For this purpose, a scalable control strategy consisting of two levels is proposed: The first level consists of the decentralized control of each rotor unit. By using an LPV formalism, it is shown how the nonlinearities of the controlled system are considered in the design using decentralized wind speed observer of each rotor to improve the overall closed-loop performance. To mitigate the lateral loads on the multi-rotor main tower caused by asymmetric rotor thrust forces, a higher-level controller is introduced. Finally, the applicability of the controller structure is demonstrated by simulation studies.

Pitch and Yaw System

Effects of wind field characteristics on pitch bearing reliability: a case study of 5 MW reference wind turbine at onshore and offshore sites

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Abstract: This paper presents a study on pitch bearing basic rating life affected by wind field characteristics at both onshore and offshore wind sites. The National Renewable Energy Laboratory 5MW reference wind turbine is selected for the study. Wind field characteristics including reference hub height mean wind speed, wind speed distribution, wind shear, and vertical inflow are studied. A decoupled approach is employed where global analysis is performed first. Second, the load effects from the global analysis are applied on a reference pitch bearing designed based on best industrial practices. For the case study onshore site, it is found that the Kernel density estimation best fits the wind distribution, while the International Electrotechnical Commission proposed distribution appears to be not suitable. Moreover, it is shown that the seed number has high effect on the bearing life in turbulence wind and the wind speeds around rated have the highest contribution in both bearing fatigue damage and extreme load failure. The results contribute to better understanding of the wind field characteristics on the pitch bearing life.

The Wind Turbine Design Guideline DG03: Yaw and Pitch Rolling Bearing Life Revisited – An Outline of Suggested Changes

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Abstract: The Design Guideline 03 (DG03) published by the National Renewable Energy Laboratory in 2009 is widely used in the wind industry. It allows engineers to get acquainted with design aspects and methodologies to determine pitch and yaw bearing static capacity and fatigue life. The combination of the detailed theoretical descriptions and practical examples makes it a highly application-oriented document. Since its publication, the knowledge about oscillating bearings, slewing bearings, and wind turbines has grown significantly. Some aspects of the DG03 need updates to reflect the current state of the art. This work covers proposed changes for an upcoming revision of DG03.

Design and calculation process for large-sized multi-MW blade bearings and product development trends

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Abstract

- Multi-bearing FE analyses and state-of-the art postprocessing of results allowing a better, more realistic evaluation of the blade bearing performance and likewise a more reliable bearing design in particular for multi-MW turbines
- Product development trends: Pitch Bearing Unit (PBU)
  - (i) providing enhanced, superior bearing system stiffness
  - (ii) bundling blade bearing and pitch drive functionalities and ultimately
  - (iii) enabling innovative supply chain modifications and transport solutions to the OEM