Gearbox Reliability Collaborative 1.5 (GRC1.5) Project: Joint Industry Megawatt Scale Gearbox Field Tests

Cooperative Research and Development Final Report

CRADA Number: CRD-16-00608

NREL Technical Contact: Jon Keller

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5000-81064
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Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

Cooperative Research and Development Final Report

Report Date: September 22, 2021

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the final CRADA report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: SKF USA Inc. (formerly SKF GmbH in original agreement)

CRADA Number: CRD-16-00608

CRADA Title: Gearbox Reliability Collaborative 1.5 (GRC1.5) Project: Joint Industry Megawatt Scale Gearbox Field Tests

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DOE Program Office:

Office of Energy Efficiency and Renewable Energy (EERE), Wind Energy Technologies Office

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$400,000.00
Year 2	$400,000.00
Year 3	$400,000.00
Year 4, Modification #1	$0.00
Year 5, Modification #1	$0.00
TOTALS	$1,200,000.00

Executive Summary of CRADA Work:

A new DOE/NREL industry collaboration called the Gearbox Reliability Collaborative 1.5 (GRC1.5) will undertake field testing on a commercial multi-megawatt wind turbine gearbox to collect loading data as installed in the turbine to thoroughly characterize gearbox loads and responses during actual in-field conditions. A chief outcome is to provide publicly available operational loading data to the industry. This will provide a greater understanding of steady-state, transient, and fault response for both the input and output of the gearbox; thus, facilitating improvements in the gearbox components, lubrication system, power converter or turbine controller.

Summary of Research Results:

The NREL Gearbox Reliability Collaborative (GRC) was initiated by the U.S. Department of Energy and developed with broad participation from the wind turbine industry to address the fact that wind turbine gearboxes are not achieving the expected 20-year design life. The GRC approach is to document and review the complete design process–from design to loads measurement to design validation – and identify the areas critical to design success that have high sensitivities or uncertainties. To date, not enough data has been collected from installed turbines to thoroughly characterize gearbox loads and responses related to premature failures of gearbox bearings during actual in-field conditions. The primary objective of this CRADA project was to measure the operational conditions on the high-speed-shaft bearings in an installed wind turbine gearbox to characterize the bearing white-etch cracking (WEC) failure mode.

SKF GmbH (SKF) and NREL collaborated under this CRADA from October 2016 to January 2021. During this period, Jonathan Keller was the NREL Principal Investigator (PI) for the project and David Vaes was the SKF PI. The objective of this work is directly related to CRADA 17-694 with Winergy, so contributions from Winergy also directly supported this CRADA with SKF. As a part of this effort, a Winergy 4410.4 gearbox with specially instrumented SKF NU 2326 ECML/L4BC3 and NU 232 ECML/L4BC3 cylindrical roller bearings (CRBs) supporting the high-speed-shaft (HSS) was installed in the DOE-owned General Electric 1.5 megawatt (MW) SLE wind turbine at the Flatirons Campus in December 2017. After commissioning, the system was used to collect gearbox and bearing data from January 2018 until the conclusion of this CRADA. The measurements were used to validate NREL and SKF bearing models. The validated models were then used to evaluate different measures of roller slip losses that are considered as potential measures of the risk of creation of white-etching cracks in wind turbine gearbox bearings. Near the end of the original 3-year Period of Performance (PoP) in October 2019, management of this CRADA was transferred to SKF USA Inc. and the PoP was extended until January 2021. At the conclusion of this CRADA, the Winergy gearbox and SKF bearings remain installed in the turbine.

Through the course of the project, multiple tasks were completed and are summarized in this final report for the CRADA. Task descriptions in this report follow the numbering in the Joint Work Statement of the CRADA.

Task 1a Engineering Support for Instrumentation Development

Includes the following three subtasks:

1. *Participate in the collaborative to identify test goals and approach*
2. *Provide input and guidance to the collaborative on bearing design and manufacturing issues*
3. *Provide detailed bearing information for instrumentation purposes – specification, loads, ratings, drawings, models.*

This task was divided into two parts. Early on in the project, SKF provided NREL engineering support in the form of detailed information, including specifications, loads, ratings, drawings, and models, on the selected SKF HSS CRBs for the purpose of developing the instrumentation for the bearings and the gearbox [1-3].

Task 2 Bearing Hardware and Instrumentation

Includes the following three subtasks:

1. *Provide test bearings for use in operation*
2. *Provide instrumentation for measurements of specific interest to the bearing supplier (i.e. roller slip, stray current, humidity and water-in-oil)*
3. *Provide in situ calibration assistance, if necessary*

In this task, SKF provided the specially instrumented, black-oxide-coated, outer-ring guided NU 2326 ECML/L4BC3 and NU 232 ECML/L4BC3 HSS CRBs as shown in Figure 1, SKF-patented inductive coils [4] to measure roller speed in as shown in Figure 2, a standard QJ 328 N2MA/C3 four-point contact ball bearing, commercial Vaisala HMP110 air humidity and MMT162 water-in-oil sensors, and three commercial Power Electronic Measurements CWT 110 stray current sensors to NREL in November 2016.

Figure 1. NU 232 (left) and 2326 (right) bearings. Photos by Jonathan Keller, NREL 40979 and 40980

Figure 2. NU 232 (left) and 2326 (right) bearing roller speed instrumentation. Photos by Jonathan Keller, NREL 40981 and 40982

The CRBs each have a magnetized roller, which when rotating next to the inductive coil measure the rotating speed of the roller. Commercial proximity switches provided by NREL detect the passing of a single metal pin in the cages each cage revolution, thus determining the average cage speeds over the revolution and indicating the precise circumferential position of the magnetized roller [5].

The modified bearings and instrumentation were installed for a “fit-and-function” check in a spare Winergy 4410 gearbox rear upper housing from November 2016 to April 2017. Required machining and instrumentation routing challenges were discovered and resolved. A small electric motor was used to spin the high-speed shaft, while recording data from the instrumentation—specifically, the shaft speed, cage speed, and roller speed instruments. Each was confirmed to be working properly in early May 2017 [5].

NREL and Winergy personnel then assembled the production gearbox with the complete HSS instrumentation package, shown in Figure 3, at the Winergy facility in Elgin, IL in September 2017. In addition to the CRB roller and cage speed measurements described earlier, the HSS speed is measured with an encoder, and HSS torque and bending moments are measured with strain gauges. Additional instrumentation measures the tribological environment of the bearings, including the bearing inner and outer ring temperatures, the lubricant temperature and water content, air temperature and humidity within the gearbox cavity with respect to the wind turbine nacelle, and any stray electrical current across the bearings [5].

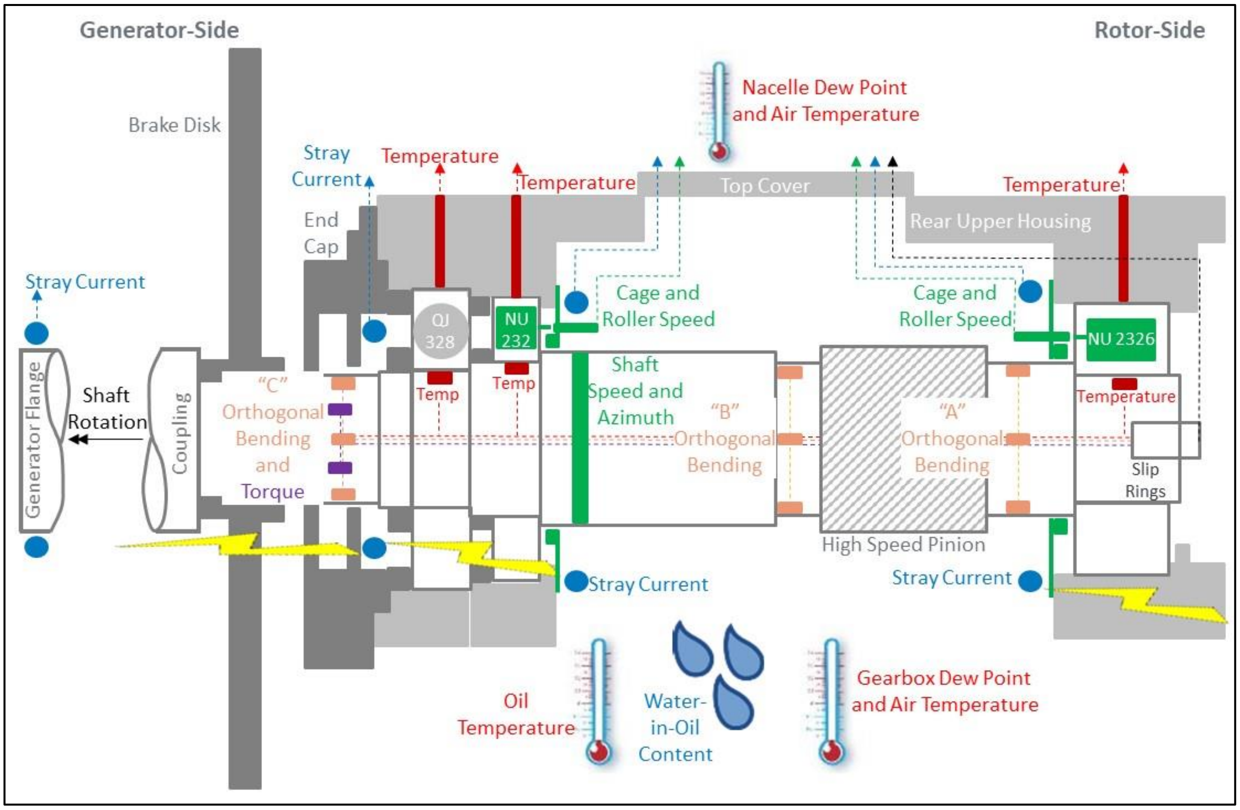

Figure 3. High-speed-shaft instrumentation schematic

Once assembled, a standard production acceptance load test was conducted on the gearbox as shown in Figure 4. The load test consisted of an initial flushing of the gearbox, followed by operation at three speed and torque settings up to rated conditions over the course of 3 hours. Data for the instrumentation described in this report were collected during the load test with a system custom-built by NREL. In this manner, the HSS torque and bending gauges were also calibrated and CRB roller and cage speeds were compared to theoretical values [5].

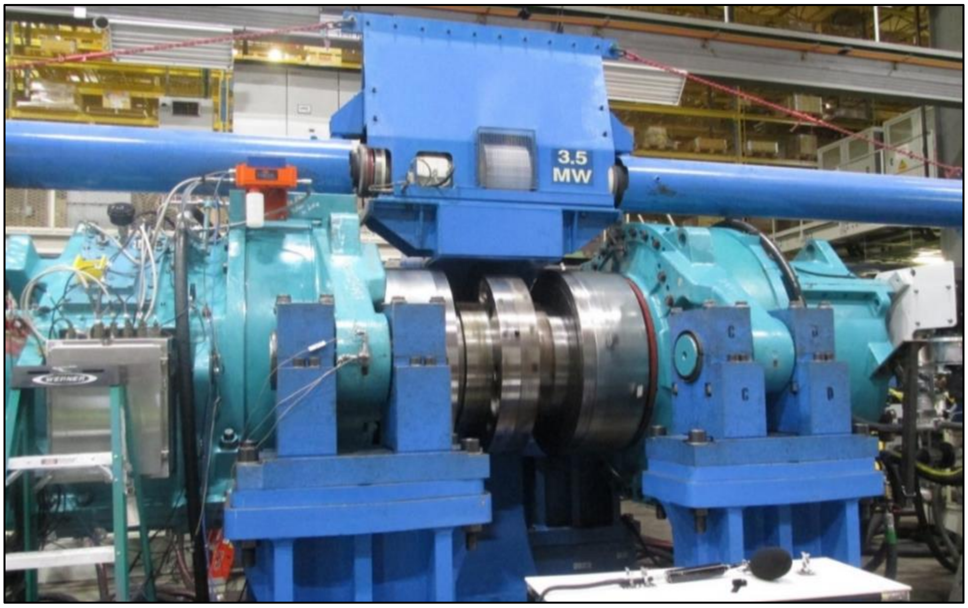

Figure 4. Production acceptance load test. Photo by Shawn Doner, NREL 50080

The gearbox was then mated with the main shaft and main bearing and then shipped to NREL. The system was then installed in the GE 1.5-MW SLE wind turbine at the NREL Flatirons campus, as shown in Figure 5, in December of 2017. Gearbox measurements are time-synchronized with measurements from previously existing instrumentation on a meteorological tower in front of the turbine and on the turbine itself, including air temperature, pressure, and humidity; wind speed and direction at several heights, plus nacelle direction, rotor speed, and blade pitch angles; main shaft, tower, and blade loads; turbine power; and several supervisory control and data acquisition (SCADA) channels. The turbine and other instrumentation were recommissioned in January 2018, with full operations beginning in February 2018 [6,7].

Figure 5. Gearbox swap (left) and installation in turbine (right). Photos by Dennis Schroeder, NREL 49409 and 49413

Since then, drivetrain and turbine measurements have been acquired over a wide range of operating conditions, including power production in normally occurring winds; parked and idling situations; and intentionally induced transient startup, shutdown, emergency stop, and grid events. From installation through January 2021 (3 full years), the turbine was operated (i.e. connected to the grid and producing power) for over 4,200 hours.

Task 1b Engineering Support for Data Analysis

Includes the following subtask:

4.Provide data analysis and interpretation supported by advanced bearing simulations

Throughout the operation of the drivetrain and turbine, SKF and NREL collaborated on analysis of the data and interpretation of the results as supported by advanced bearing simulations. Initial analysis focused on developing a thorough understanding of the cage and roller speed data and its processing, along with the main shaft and HSS torque and speeds. This data analysis was supported by development of the bearing models. Processing of the cage and roller speed data, in particular, requires processing of the "raw" roller speed signals, calculation and correlation of the roller speed with the estimated azimuthal position of the roller derived from the cage speed, and averaging of the roller speed over multiple revolutions of the roller [8-11].

Along with thorough vetting of the experimental data, SKF and NREL developed models to simulate the HSS CRB operating conditions, including the applied bearing loads, load distribution through the bearing rollers, and the bearing and cage rotational speeds – and consequently, the amount of roller slip in the bearings. The SKF model was developed in the BEAring Simulation Tool (BEAST), an SKF proprietary software that can simulate systems of bodies in a fully transient domain. Each bearing component (i.e. rolling elements, cage, and rings) is modeled as an independent body that interacts via contacts or simpler laws with the other bodies and the environment. The two CRBs in the detailed SKF BEAST model are shown in Figure 6, along with the bearing load distribution for near-rated operational conditions. The HSS itself is considered rigid, with the gear loads and moments applied at the center line [8-11].

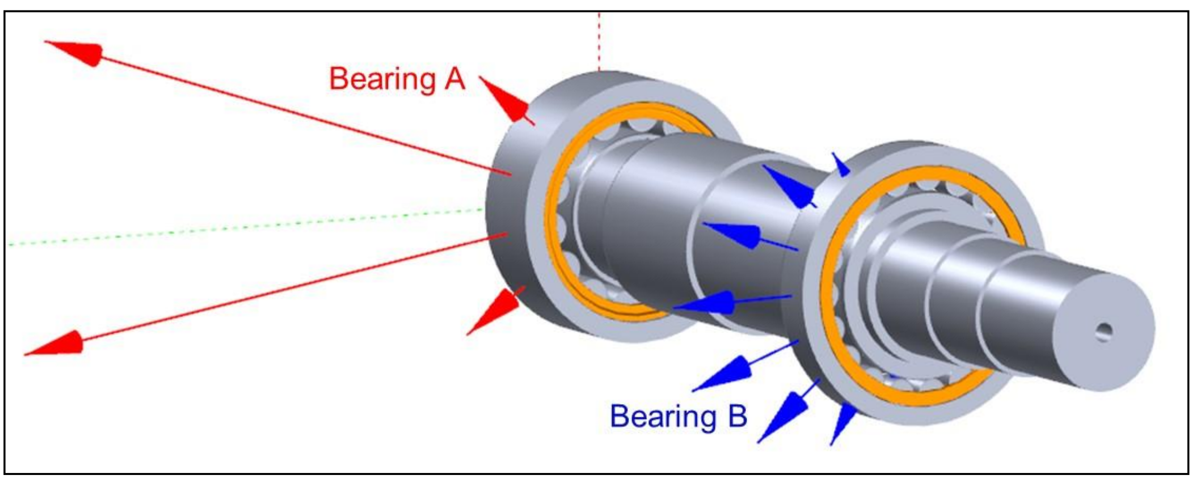

Figure 6. BEAST HSS model and bearing roller-raceway forces for near-rated torque

The NREL model consists of a combination of two previously published analytical bearing models. With these models, the equations of motion are developed for the cage and rollers from the free-body diagrams shown in Figure 7. The CRB roller loads are the most important input to the model. They are derived from the CRB radial loads, which are estimated from the gear and shaft geometry and loads. The roller loads, lubricant temperature and shaft speed are then used to calculate the cage speed, friction between the cage and raceway, and roller speed for the most highly loaded roller. These outputs are then used to calculate the friction between the cage and rollers and, finally, the individual roller speed over its orbit. The analytical model can be used for both steady-state and dynamic operating conditions [10-13].

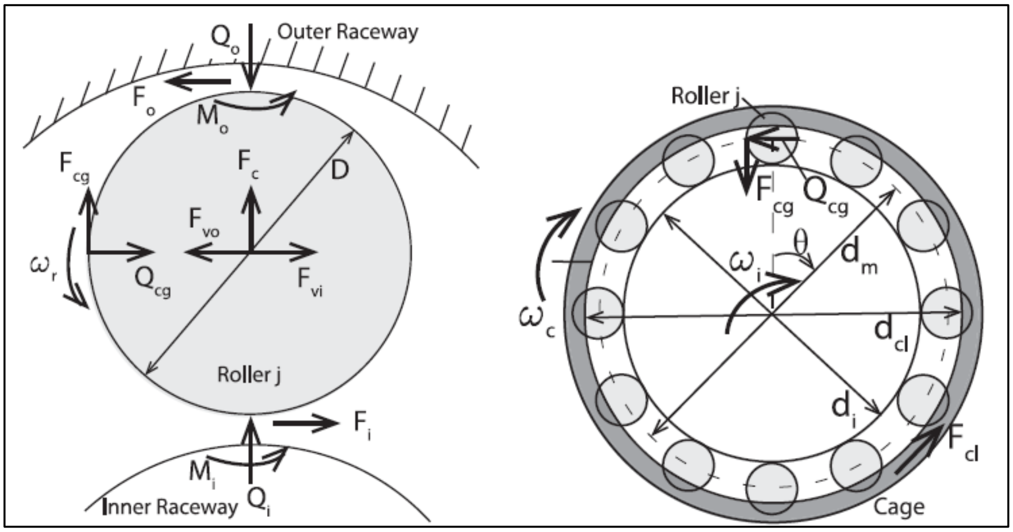

Figure 7. Fee-body diagram of a roller (left) and cage (right) in a CRB

An example comparison of the measured data with modeled results is shown in Figure 8 for both bearings [10,11], A and B shown in Figure 1. Overall, there is good correlation. The two numerical methods do show differences with the measured roller speed for both bearings. An important consideration in modeling the roller speeds and loads is the bearing operating clearance, which is largely a function of the bearing temperature and the rate of deceleration of the rollers in the unloaded zone.

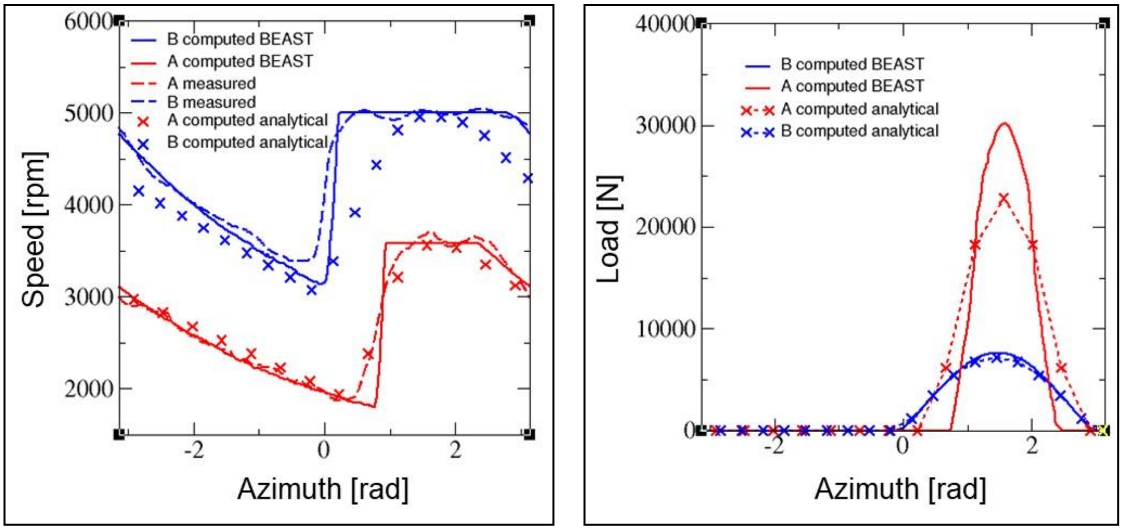

Figure 8. Roller speed (left) and load (right) for near-rated torque for 80% torque

The NREL analytical model was further validated across a wider range of turbine load and speed operating conditions, lubricant temperatures, and some transient events [13]. These conditions emphasize the importance of friction between the cage and rollers and the cage and rings (i.e. cage-landing friction). The predicted cage and roller slip compared to the measured results with reasonable accuracy across a wide range of near steady-state operating conditions and transient events. At its best, the analytical model predictions match experimental measurements within 10% for lubricant temperatures above 40° C and wind speeds over 10 meters-per-second (m⁄s). In steady-state conditions at low wind speeds and low lubricant temperatures, cage and roller slip up to 60% occur in the loaded zone of the bearing, indicating that none of the rollers even come close to pure rolling conditions. In the unloaded zone, up to 80% roller slip occurs. Cage and roller slip then decrease as the lubricant temperature and wind speed increases as shown in Figure 9. Depending on the wind speeds and lubricant temperature, these conditions could occur for extended periods in both normal operations and start-up conditions. Bearing slip is exacerbated by low oil temperatures that might more frequently occur in colder climates. This work led to the development of a Software Record (SWR) 20-34 titled “Roller Slip Simulator for Cylindrical Roller Bearings”.

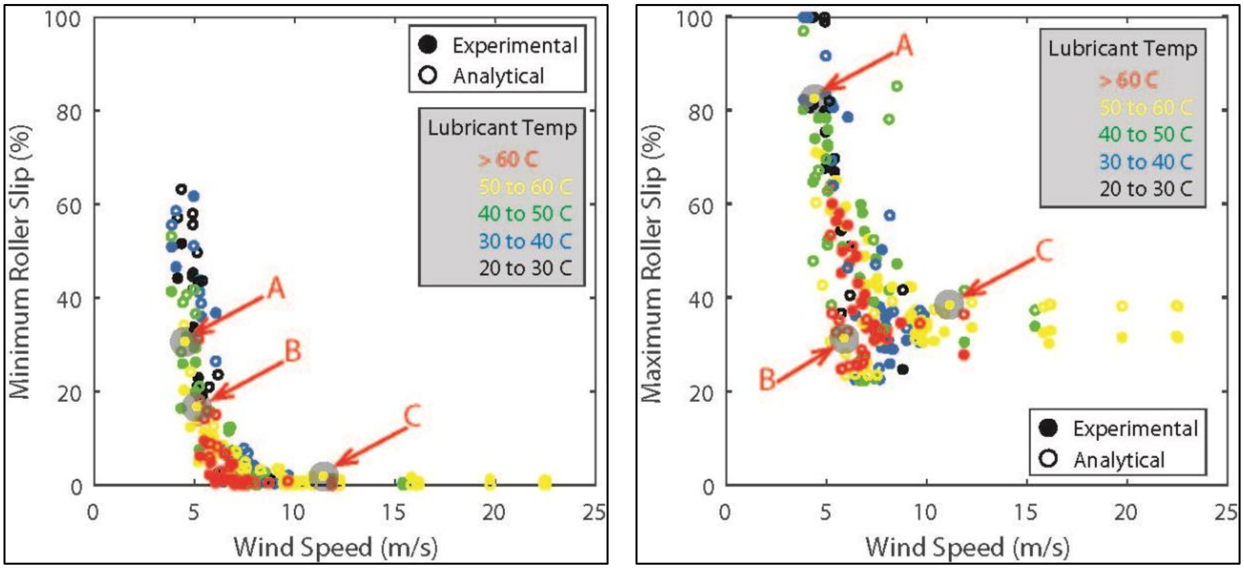

Figure 9. Minimum (left) and maximum (right) roller slip during normal power production

After validation of the roller slip models, they were used to evaluate the roller slip losses or cumulative frictional energy that are considered potential driving factors for WECs in wind turbine gearbox bearings [10,11,14]. As a measure to evaluate the risk for roller slip induced failures, the power slip density in the contact (in units of power in watts (W) per unit area in square millimeters (mm^2)), or and cumulative frictional energy (in units of joules (J)) or joules per second (J/s)) between the roller and inner raceway were used.

As shown in Figure 10, the larger power slip density peak is always at the entrance of the loaded zone where the acceleration is the largest. The power slip density is generally higher in bearing A because it has larger rollers that offer more inertia against the friction force in the contacts. The cumulative frictional energy is a function of friction coefficient, normal load, and difference in velocity between two sliding surfaces over a period of time. Similar to the power slip density, both bearings accumulate the most frictional energy when entering the loaded zone because of the significant roller sliding. A much smaller amount of frictional energy is accumulated when exiting the load zone. The overall amount of energy accumulation in bearing A is more than twice bearing B.

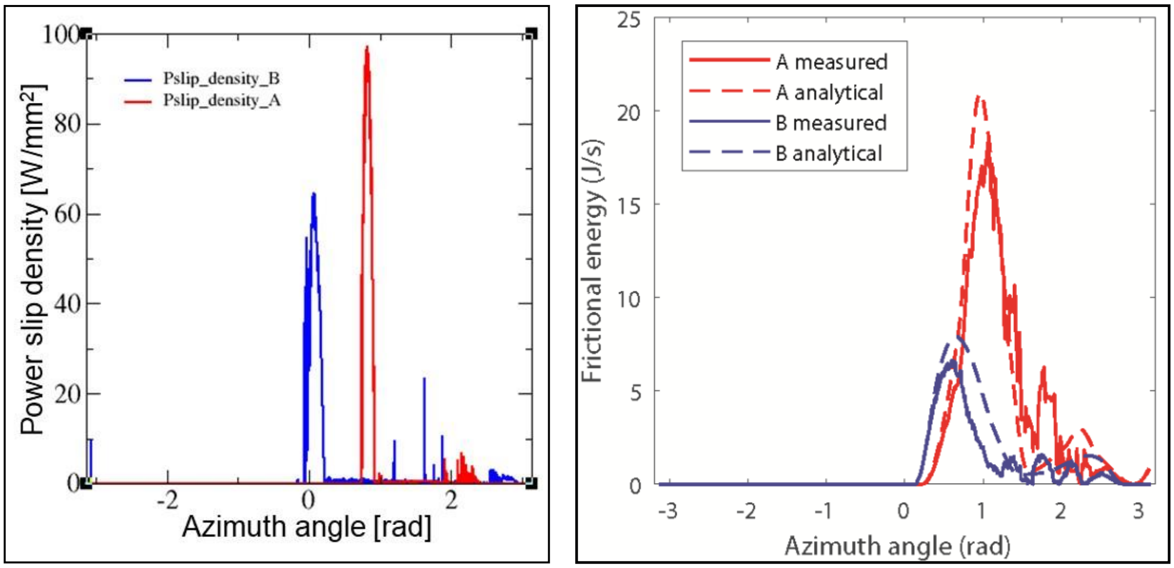

Figure 10. Power slip density (left) and cumulative frictional energy (right) for 80% torque

Because the combination of analytical models quickly estimates the bearing roller and cage speeds and the extent of roller slip, it is suitable for inclusion into models that assess the probability of failure (PoF). An interdisciplinary methodology to calculate the probability of failure of wind turbine gearbox bearings was then developed [14-18]. Assuming that the cumulative frictional energy is the mechanism causing bearing WEC, the methodology was used to calculate the probability of failure of each bearing in each gearbox in each turbine of an operational wind plant and compared to failure records over 10 years of operation of the plant as shown in Figure 11. Through statistical analysis of historical data, the methodology enables reliability assessment of axial cracking in individual wind turbine bearings and connects the reliability forecast with turbine design and operations.

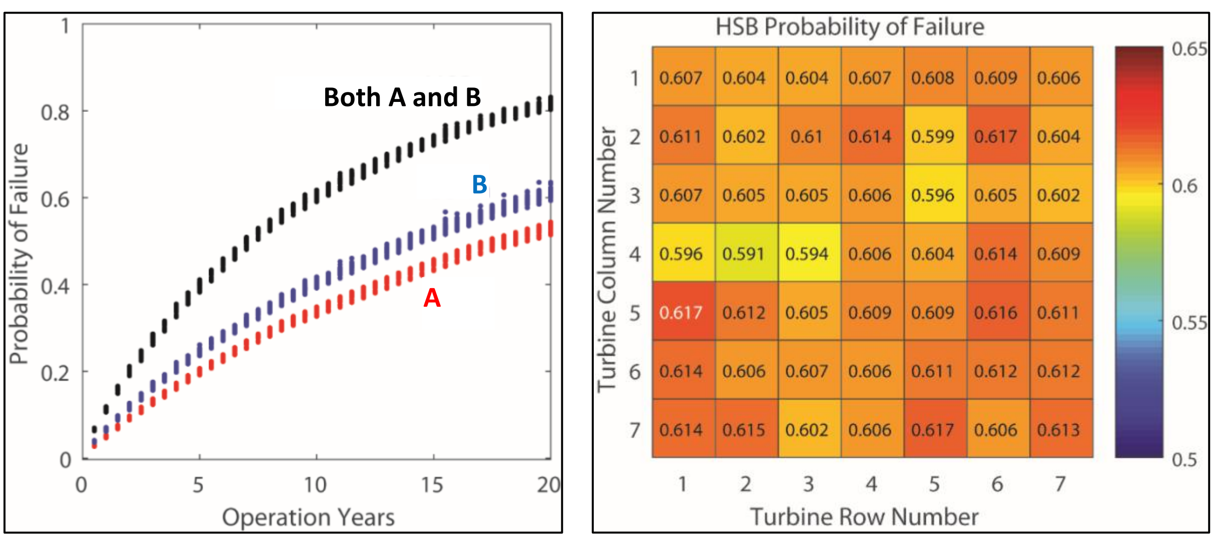

Figure 11. Probability of failure over time (left) and heat map (right) for cumulative frictional energy

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Subject Inventions Listing:

None

ROI #:

None