WhiteWind: White Etching Crack (WEC) Bearing Failures in Wind Turbines

Cooperative Research and Development Final Report

CRADA Number: CRD-18-00758

NREL Technical Contact: Jonathan 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

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5000-81232
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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

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Cooperative Research and Development Final Report

Report Date: September 23, 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: Technical University of Denmark (DTU)

CRADA Number: CRD-18-00758

CRADA Title: WhiteWind: White Etching Crack (WEC) Bearing Failures in Wind Turbines

Responsible Technical Contact at Alliance/National Renewable Energy Laboratory (NREL):

Jonathan Keller | jonathan.keller@nrel.gov

Name and Email Address of POC at Company:

Anand Natarajan | anat@dtu.dk

Sponsoring 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 Year 2, Modification #1 and #2 Year 3, Modifications #3	$146,000.00 $0.00 $(46,000.00)
TOTALS	$100,000.00

Executive Summary of CRADA Work:

A WEC is a particularly aggressive, unpredictable and wide spread rolling element bearing failure mode that is common for large multi-megawatt (MW) wind turbines. WEC is considered the single most expensive failure mode for all wind turbine components, and there is currently no commercial solution. The Technical University of Denmark (DTU) is leading the WhiteWind project to investigate WECs through funding provided by the Innovation Fund Denmark. Other project partners include Vestas, SKF, Expanite, Rheinisch-Westfälische Technische Hochschule Aachen University (RWTH Aachen), and Argonne National Laboratory. The objective of the overall project is to develop a new surface engineered WEC-resistant bearing material using novel surface engineering techniques that shall provide a commercially competitive alternative to existing wind turbine bearings. NREL will support the project by providing existing measured bearing loads and validating models of drivetrain loads.

Summary of Research Results:

The NREL Drivetrain Reliability Collaborative (DRC) was initiated by the U.S. Department of Energy (DOE) 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. Through a DOE program that includes two other CRADAs (CRD-16-608 with SKF GmbH and CRD-17-694 with Winergy Drive Systems Corporation), an instrumented 1.5 MW commercial drivetrain was installed in the DOE-owned 1.5 MW turbine in late 2017 at the National Wind Technology Center (housed at the Flatirons Campus). Gearbox operational conditions, including load, speed, and temperatures suspected of being related to the formation of WECs were measured along with the meteorological and turbine operating conditions from 2018 through 2020.

NREL and DTU collaborated under this CRADA from September 2018 to March 2021. During this period, Jonathan Keller was the NREL Principal Investigator (PI) for the project and Anand Natarajan was the DTU PI. NREL and DTU analyzed the measured 1.5 MW wind turbine operational drivetrain load and speed data. Each performed model validations using these data and a new hypothesis based on the inner raceway normal contact load magnitude at the time of roller slip was proposed as the probable cause of WECs. DTU further modeled another commercial turbine and drivetrain for the larger “WhiteWind” project effort. 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 Joint Work Statement of the CRADA.

In the first two years of the CRADA, NREL measured load, speed, turbine, and meteorological tower measurements on the drivetrain installed in the 1.5 MW turbine at the National Wind Technology Center as shown in Figure 1. NREL provided all non-protected measurement data to DTU and other project partners. 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 [1]. Drivetrain and turbine measurements were 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.

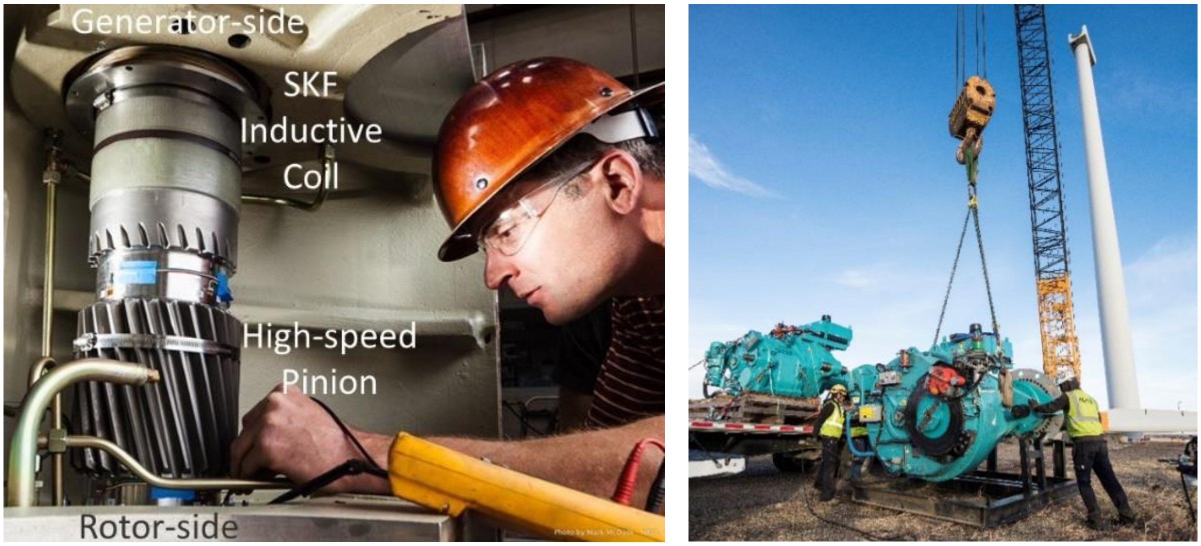

Figure 1. Gearbox instrumentation (left) and installation in GE 1.5-MW wind turbine (right). Photos by Mark McDade, NREL 49050, and Dennis Schroeder, NREL 49409

Throughout the operation of the drivetrain and turbine, DTU and NREL collaborated on analysis of the data and interpretation of the results as supported by advanced simulations. DTU and NREL each developed a 1.5 MW wind turbine aeroelastic model and detailed multi-body model of its gearbox and bearings. NREL made available relevant OpenFAST aeroelastic simulation results from the turbine model [2]. DTU then used the measured loads supplied by NREL to validate the simulated loads obtained from their multi-body model of the 1.5 gearbox.

NREL also analyzed rolling element slippage data from the test measurements and developed and validated a roller slip model that included the applied bearing loads, load distribution through the bearing rollers, and the bearing and cage rotational speeds [3]. The NREL model [4,5] 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 2. The bearing roller loads are the most important input to the model. They are derived from the bearing 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.

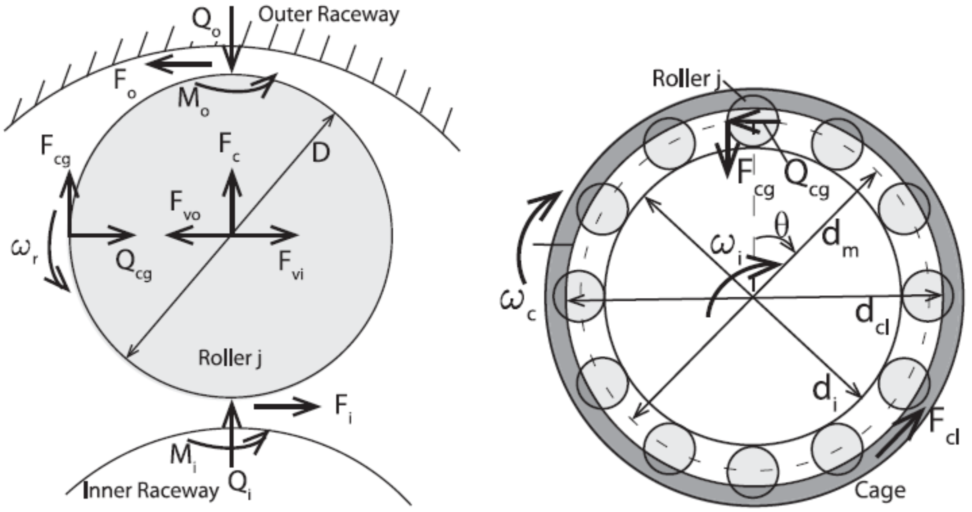

Figure 2. Free-body diagram of a roller (left) and cage (right) in a cylindrical roller bearing [5]

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 as shown in Figure 3. At its best, the analytical model predictions match experimental cage and roller slip measurements within 10% for lubricant temperatures above 40° C and wind speeds over 10 meters-per-second (m⁄s). The validated roller slip model was used to evaluate the cumulative frictional energy damage criteria as a potential driving factor for WECs [6].

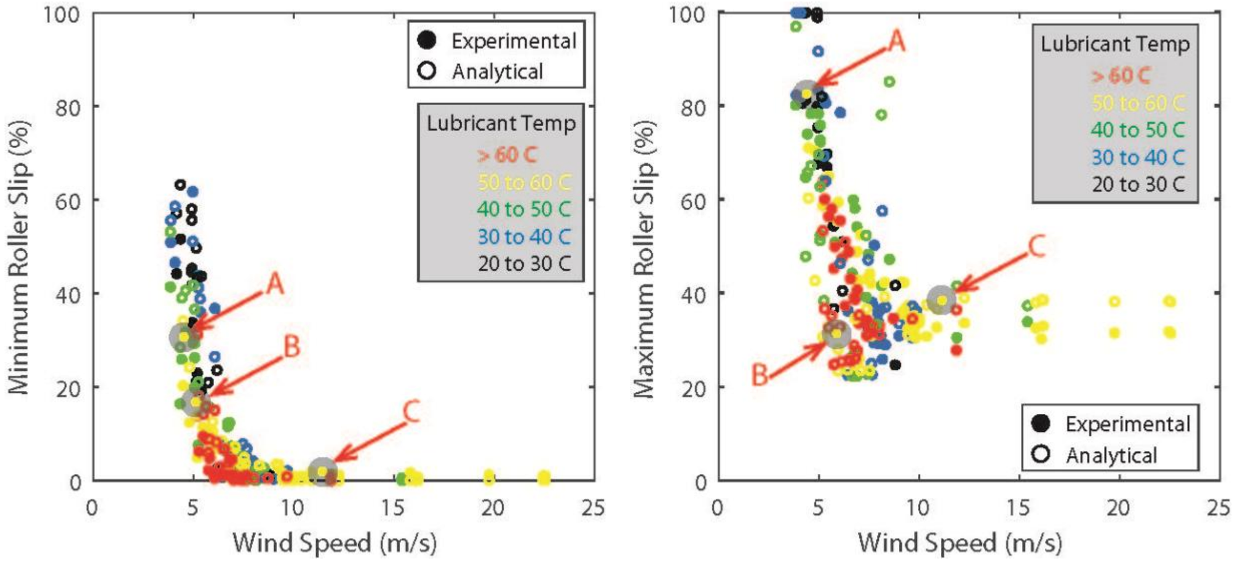

Figure 3. Minimum (left) and maximum (right) roller slip during normal power production [5]

DTU used these results to compare against its own analytical model prediction of roller slip in different bearings. This work was based on measurements of a Vestas V52 850-kilowatt turbine installed at the Technical University of Denmark Risø campus. The gearbox speed was measured using a speed sensor, strain gauges were used for measuring the shaft torque, and laser sensors were used to measure the shaft horizontal and vertical displacements. These measured quantities were then used for estimating the bearing roller slip using an analytical model [7,8], based on another model for a different bearing type. This model assumes rigid-body, in-plane motion of the bearings and neglects the effects of bearing radial clearance and fluid lubrication. A schematic of a tapered roller along with its characteristic dimensions and coordinate system is shown in Figure 4. By considering the semicone angle of the inner and outer raceways, α and β, the semicone angle of the roller, □, and neglecting the flange contact forces, the governing equations can be obtained for the bearing by using a force equilibrium approach.

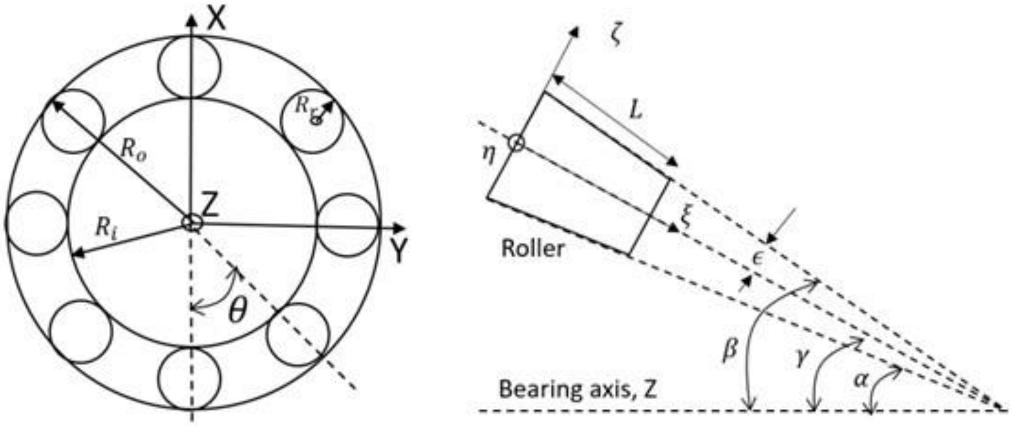

Figure 4. Minimum (left) and maximum (right) roller slip during normal power production [7]

With the developed roller slip models, a new hypothesis was developed to describe the formation of WECs based on the maximum bearing contact load during roller slip. The following steps were developed to identify the WEC causing events:

- the roller-to-inner raceway contact loads and roller slip were determined for each mean wind speed
- the peak contact load during roller slip was selected over 10-minute time intervals
- the local cumulative probability of the peak load was obtained using the median rank of the sorted peak loads over multiple repetitions of the interval
- the corresponding 10-minute probability of the peak contact load was calculated
- the 10-minute probability can be combined with the annual probability of occurrence of the mean wind speed to determine its corresponding annual probability
- a limiting probability of the 10-minute peak contact load during slip is specified, which can be used as an acceptable design criterion.

For the studied wind turbines, a Rayleigh distribution of the Class II wind speed defined in IEC 61400-1 was assumed and a Gumbel distribution with a quadratic exponent was used to fit the probability of exceedance of the peak contact load at each mean wind speed. Figure 5 shows the probability of exceedance of the maximum contact load at the time of slip during normal power production for the Vestas V52 and GE 1.5SLE turbines. A 1-month return period of the maximum contact was chosen as the limiting load criteria for the WEC-inducing slip, as an example. The V52 requires about a 40% higher load than observed in simulations for this WEC criteria to hold, whereas the GE 1.5SLE requires an 18% higher load than observed in the data set for this WEC criteria to hold [7,8]. The damage criteria of the predicted 1-month extreme contact load can be continuously tracked using real-time measurements with updated simulations to determine if it exceeds a threshold load value, which is indicative of WEC onset. This provides a viable quantitative methodology to assess operating conditions as to whether they may induce WECs in the bearing.

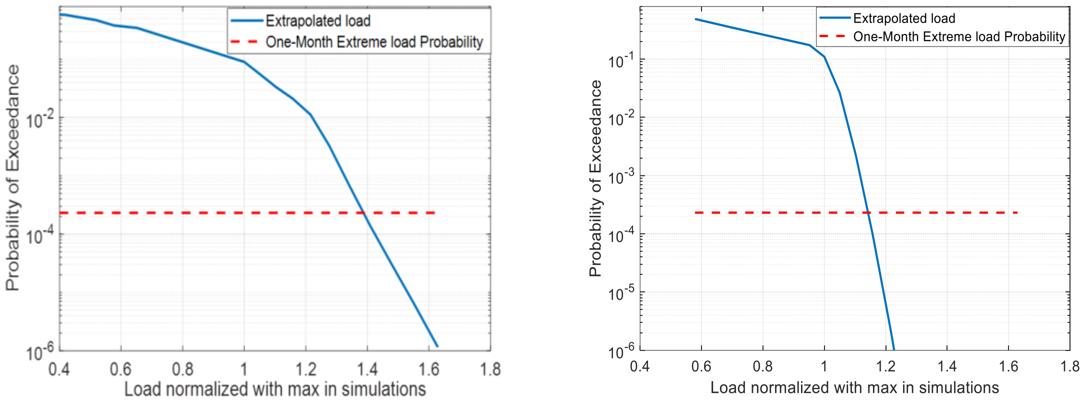

Figure 5. Probability of exceedance of the maximum roller contact load over the roller slip cases in the loaded zone for a month maximum for the Vestas V52 (left) and GE 1.5 (right) [7]

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Subject Inventions Listing:

None

ROI #:

None